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Biomechanical constraints on intra-limb coordination in boys with and without development coordination disorder

Asmussen, Michael James

BIOMECHANICAL CONSTRAINTS ON INTRA-LIMB COORDINATION IN BOYS WITH AND WITHOUT DEVELOPMENTAL COORDINATION DISORDER

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by

Michael James Asmussen

Supervisor: Dr. Eryk Przysucha

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Abstract

It is known that children with DCD have difficulties organizing actions involving coordination between limbs or limb pairs (e.g., Astill, 2007; Volman, Laroy, & Jongmans, 2006). It is also apparent that a coalition of constraints forces certain movement patterns to emerge at any level of organization (Newell, 1985). No research has examined how children with and without DCD solve the degrees of freedom problem, in the face of relevant constraints, during uni-manual goal-directed actions. The purpose of this study was to determine differences in the nature and effectiveness of intra-limb coordination, and underlying biomechanical constraints, in children with (*M* = 11.0 years, *SD* = 1.16) and without (*M* = 10.6 years, *SD* = 1.08) DCD, in one-handed catching. Nineteen boys, ten with and nine without DCD, attempted ten catches at 7m/s. In terms of effectiveness, the results showed that children with DCD caught fewer balls (32%) compared to their typically developing peers (85%). Behaviourally, children with DCD exhibited a universal tendency to decouple the relevant joints. Typically developing children, on the other hand, coupled and decoupled the respective joints, indicating that there is no one universal intrinsic tendency to coordinate joints at the intra-limb level of organization demonstrated by this sample. Aside from differences in coupling, children with DCD exhibited less stable spatial relations of the joint pairs, indicating that they did not exhibit a consistent movement pattern across trials. These differences in coordination also coincided with different torque modulation tendencies. Children with DCD utilized less passive torque across all the relevant joints and more muscular torque at the most distal joint (i.e., the wrist), which coincided with decoupling the elbow-wrist joint pair. Overall, it was concluded that, during intra-limb coordination, biomechanical constraints, namely torque modulation and joints involved, are one

of the many potential factors that contribute to qualitatively different movement patterns in children with DCD.

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Table of Contents

List of Key Definitions

Active torque: Force produced about a joint from muscles, tendons, or ligaments involved (Hollerbach & Flash, 1982).

Bi-articular muscles: Muscles that span two joints (i.e., biceps brachii) (Van Ingen Schenau, Bobbert, & Rozendal, 1987).

Biomechanical constraints: Limitations imposed on the emerging action due to structural properties of body, as well as the nature of torque production (Dounskaia, Ketcham, & Stelmach, 2002).

Control (flexibility): The parameterization of scalar quantities to allow for spatial/temporal relations to remain intact across varying task demands (Newell, 1986).

Constraints: Factors that force certain movement patterns to emerge over others, even though more than one movement solution could be performed (Bernstein, 1967).

Coordination: The degree and stability of spatial and temporal relationships between two or more elements in a system, resulting in a functional movement pattern (Newell, 1986).

Degrees of freedom: The number of ways a system can vary, or the number of planes in which a joint can move (Bernstein, 1967).

Extrinsic coordinates (or Cartesian coordinates): An external reference frame that trajectory is planned in regards to the end effector (e.g., hand or foot) (Soechting, 1989).

Intra-limb coordination: Spatial/temporal relationship between joints of a single limb (i.e. muscles or joints) (Soechting & Lacquaniti, 1981).

Intrinsic coordinates: An internal reference frame that the Central Nervous System (CNS) utilizes to organize the emerging action. In the context of the human body, the location of one joint in relation to another (e.g., shoulder relationship to the elbow) (Soechting, 1989).

Net torque: Overall torque produced at a joint that leads to joint displacement. This torque is made up of both active and passive forces (Hollerbach & Flash, 1982).

Passive torque: Torque produced about a joint that is due to gravitational and centripetal/Coriolis force, as well as inertial properties of other segments involved in the action (Hollerbach & Flash, 1982).

Stability: Consistency of a coordination pattern across trials (intra-trial variability) (Haken, Kelso, & Bunz, 1985).

Synergies or Coordinative structures: A functional, stable relationship between two or more joints/body segments in time and space (Bernstein, 1967).

Chapter 1: Introduction

Developmental Coordination Disorder

Developmental Coordination Disorder (DCD) is a deficit that affects approximately 10 to 15 percent of school-age children (Henderson & Sugden, 1992). Past research shows that boys are affected more than girls (Kasdesjo & Gillberg, 1998). The focal point of screening and diagnosis is the fact that children with DCD perform actions that are qualitatively different than those exhibited by typically developing, age-matched children (e.g., Van Waelvelde, De Weerdt, De Cock, & Smits-Engelsman, 2004). To be clinically diagnosed with DCD, a child must meet four criteria as stated by the Diagnostic and Statistical Manual of Mental Disorders (DSM IV; APA, 2000). He/she must underperform in activities of daily living that require motor coordination, when compared to his/her age matched peers. The emerging coordination problems must have a direct impact on academic achievement and/or activities of daily living, and cannot be caused by any known medical condition (e.g., Pervasive Development Disorder). If a cognitive delay is present, the difficulties in coordination are in excess of the problems associated with that particular impairment (APA, 2000, pg. 58).

Children with DCD could also have numerous concomitant disorders that could further affect their coordination problems. Kadesjo and Gillberg (1998) examined this issue and found that approximately half of the children also had some form of attention deficit hyperactive disorder (ADHD). In addition, children with DCD may also exhibit reading difficulties (RD) that in combination with ADHD, could contribute to physically awkward movement patterns (Crawford & Dewey, 2008). It is evident that there are numerous factors contributing to coordination problems in children with DCD, ultimately making it difficult to localize the most pertinent limiters on their performance.

The existing research, in the motor control domain, has focused on sensory, perceptual, and perceptual-motor issues that children with DCD exhibit when performing numerous tasks. These issues have been examined in tasks such as balance or postural control (Geuze, 2003; Geuze, 2005; Przysucha & Taylor, 2008), isometric one degree of freedom tasks (Oliveira, Shim, Loss, Peterson, & Clark, 2006; Smits-Engelsman, Westenberg, & Duysens, 2008), continuous actions (Volman et al., 2006; Volman & Geuze, 1998a), and goal-directed actions (Johnston, Burns, Brauer, & Richardson, 2002). Limited research, however, has examined motor issues exhibited by these children. More specifically, little is known about how biomechanical or neuromuscular (Huh, Williams, & Burke, 1998) constraints affect the nature of goal-directed actions in children with DCD. Wright and Sugden (1996) completed a cluster analysis and revealed that ball catching is one task in which the majority of children with DCD perform poorly. Since many children with DCD have problems catching a ball, understanding the difficulties this population has performing this action may provide a *window* into problems exhibited by a large portion of this diverse population.

Coordination

When catching a ball, one important motor issue is how the CNS organizes the relevant components (i.e., joints) to position the hand correctly in space and time. For this appropriate end-effector position to emerge, the CNS organizes a number of mechanical degrees of freedom into a functional synergy (coordinative structure). When children with DCD organize these mechanical degrees of freedom, past research has shown that they exhibit different coordination patterns and have difficulty performing the same movement pattern consistently across time/trials (e.g., Utley & Astill, 2007; Volman & Geuze, 1998a; Volman & Geuze 1998b).

To produce a functional uni-manual action, namely to catch a ball with one-hand, the CNS must coordinate different joints effectively. As seen in *Figure 1*, coordination and control at the intra-limb level, represents the most rudimentary aspect of organization that has to be acquired before higher levels of organization are achieved. Although seemingly simple, the process of coordinating joints within a limb is an intricate problem for the CNS because there are multiple mechanical degrees of freedom within each joint.

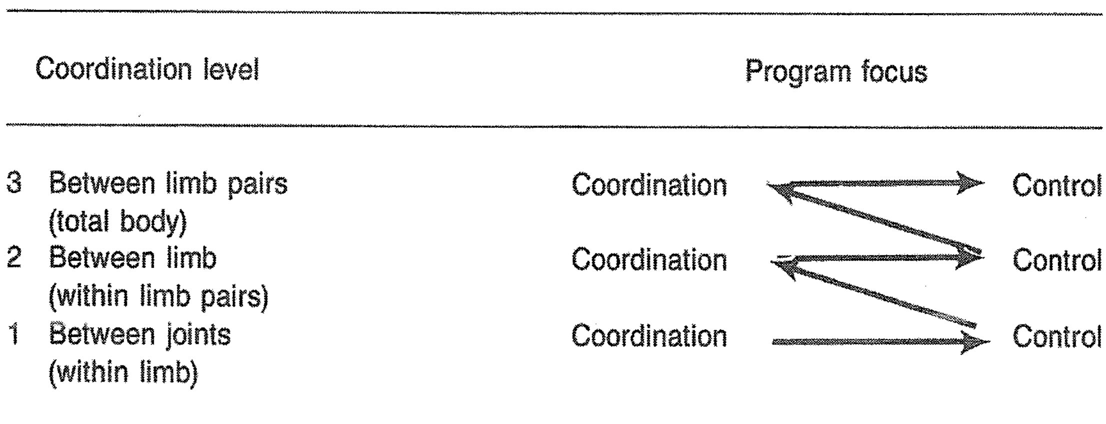

Figure 1. The hierarchical model of organization. Reprinted with permission from "Applying principle of coordination in adapted physical activity" by A. W. Burton (1990). *Adapted Physical Activity Quarterly, 7*, p. 136.

This *problem* is known as the degrees of freedom problem (Bernstein, 1967). There are seven degrees of freedom in the arm: three in the shoulder, one in the elbow, and three in the wrist. In most goal-directed actions, however, there are only six degrees of freedom required to achieve the intended goal (Soechting, 1989). For example when reaching for a cup on a table, the cup could be placed in any location in relation to the x, y, and z plane to determine where the hand has to travel in Cartesian coordinates. Also, the cup could be orientated with three degrees of freedom about the axis of rotation (i.e., sagittal, horizontal, or frontal plane). Since the arm has seven degrees of freedom, there are excess possibilities around which joints can be configured when an action is performed (Soechting, 1989). The presence of these redundant degrees of freedom makes it complicated for the CNS to organize a consistent movement pattern given a particular task goal.

To make it easier to perform a particular task, the CNS organizes the joints into functional units of action, known as synergies of coordinative structures, instead of controlling individual joints and their respective degrees of freedom. Bernstein's (1967) notion of synergy was further developed by Gelfand and Tsetlin (1966) and by Latash (2008) leading to a new concept of synergies (*Note*: *Bernstein put forth the notion of synergies first, even though his work was not published until 1967 in English*). Latash (2008) stated that a combination or group of elemental variables (i.e., joints, muscles) must meet three criteria to be coined a synergy. First, there must be a relationship among relevant variables in order to achieve the task effectively. For example, the angular displacement of the shoulder and elbow joints could form a relationship to transport the arm during a reaching task. Second, error compensation must be present between the elemental variables. This statement means that if there is an error in shoulder angular displacement, during an action, the elbow joint will compensate to ensure the task is completed effectively. Third and probably the most important feature is task dependency. This concept infers that the same group of elemental variables can be organized into a different synergy if a novel task is present. For example, the elbow and wrist joint can be organized differently to point to a target as opposed to catching a ball.

Synergies can evidently be organized at different levels (i.e., muscles, joints) (see Latash, 2008 for review). Bernstein (1967) proposed that due to lack of one to one relations between muscles and behaviour, actions are likely organized at the kinematic level. To organize movement trajectory in uni-manual tasks, the CNS must complete an inverse kinematics calculation to determine the required joint angles, in space and time, to define the emerging action (Soechting, 1989). This process is also known as joint space organization and it represents an effective method to examine how synergies form or change due to practice or development.

Although synergies, or coordinative structures (Kugler, Kelso, & Turvey, 1980), make movement organization easier for the CNS, they only partially solve Bernstein's problem (1967). Synergies do not fully solve this problem because the movement pattern that eventually emerges when performing a task depends on many other factors that exist in a particular context. These factors are known as *constraints*. In the case of children with DCD, the organization of their actions is hypothesized to be dependent on a coalition of constraints (Newell, 1985). During uni-manual goal-directed actions (i.e., one-handed catching), biomechanical constraints are a particularly important one. For this reason, it is necessary to study the degree (spatial-temporal relations) and stability (intra-subject variability) of coordination patterns, and underlying constraints (i.e., biomechanical), during goal-directed actions in children with DCD.

Constraints

The CNS can configure the joints a number of ways when performing an action. Why is it then that given an infinite number of potential possibilities, people of similar skill level perform actions in a comparable way? Many theories/models have attempted to address this redundancy problem (Haken et al.,1985; Uno, Kowato, & Suzuki, 1989). One particular model of interest, put forward by Karl Newell (1985), states that a coalition of constraints *force* the CNS to organize a unique action when many are possible. Individual, environmental, and/or task factors can all impose limits on the emerging action and affect the nature of spatial-temporal relations (i.e., synergies) between the respective elements (Newell, 1985). When examining voluntary movements, it is important to delineate the most influential constraints and understand how they affect the process of organization in different populations (i.e., children with DCD).

Task constraints. One particular limiter that affects the number of possible joint configurations is the task goal. This constraint alone does not ensure a unique movement pattern will emerge (Heuer, 1996). The nature of the task, however, can reduce the number of potential configurations substantially. For example, if a person was to grab a stationary ball, there are numerous joint configurations that can complete this task; if the ball was projected to a person with a certain trajectory, however, the number of possible joint configurations is reduced. Generally, when the task constraints are enhanced the number of possible functional solutions decreases.

To understand how movements are organized for a particular task, the spatial-temporal aspects of emerging movement form can be examined. Temporal coupling can be used to study intra-limb coordination, but it is methodologically complicated, and is difficult to infer qualitative differences of emerging movement pattern. On the other hand, spatial characteristics of movement organization play a large role at the intra-limb level of coordination. Spatial characteristics examine how the joints are organized in either an extrinsic or intrinsic frame of reference. Studying these characteristics using kinematics makes it easier to infer movement behaviour. Ultimately, how certain spatial aspects emerge during uni-manual actions is due to the nature of the task (i.e., task constraints).

The original research conducted by Soechting and Lacquaniti (1981) examined the existence of invariant spatial relationships between the joints during goal directed reaching. Invariant, or essential, relationships give insight into the parameters the CNS must consider when organizing actions. During simple reaching, angular displacement of the shoulder and elbow are *tightly* coupled, meaning that as one joint moves in space so does the other. This relationship is invariant across people with similar skill levels and different task demands (e.g., different movement speeds) (Soechting, 1984). Despite the fact that many possible joint configurations (e.g., degree of coordination) could emerge, only one was evident (i.e., tight shoulder-elbow coupling). Thus, the relationship between the shoulder and elbow represents an essential unit of action when performing goal-directed pointing/reaching actions (Bernstein, 1967). Another important characteristic of uni-manual goal-directed actions is the relationship between the elbow and wrist joint. Similar to the shoulder-elbow spatial relations, the elbow and wrist joints are also controlled as one coordinative structure, however, the degree of the emerging coupling is smaller. The elbow-wrist relationship was weaker in past research (Lacquaniti & Soechting, 1982) because the magnitude of angular displacement of the wrist (i.e., range of motion) was smaller and the wrist was controlled more independently.

As suggested by the previous literature (Lacquaniti & Soechting, 1982; Soechting & Lacquaniti, 1981), the spatial relationships between the shoulder-elbow and elbow-wrist are invariant during unrestrained reaching/pointing actions. These essential features, however, could have emerged because of the task goal (i.e., task constraints). During a one-handed catching task (Mazyn, Montagne, Savelsbergh, & Lenoir, 2006), the participants exhibited tight coupling between the elbow-wrist and the shoulder-elbow joints. As the task became harder (i.e., ball speed increased) the degree of elbow-wrist coupling increased. In addition, the nature of elbow-wrist coupling during one-handed catching (Mazyn et al., 2006) was different than uni-manual reaching (Lacquaniti & Soechting, 1982). These differences exemplify that the task (i.e., reaching vs. slow catching vs. fast catching), changed the essential relationship between the elbow-wrist from weak to tight coupling. Ultimately, the nature of spatial coupling, and essential variables, is largely dependent on the task goal, and the notion of universal invariant relationships is arbitrary rather than constant across different tasks.

Individual constraints. Task constraints are not the only factors that affect the nature of coordination (i.e., spatial relationships) between joints. A coalition of task and individual constraints force unique movement patterns to emerge. Individual or structural constraints can be defined as *hard* or *soft* in nature (Heuer, 1996). Soft constraints are associated with preferred coordination tendencies (or intrinsic dynamics) that are utilized to achieve a task goal. Bernstein's original hypothesis (1967) is that as people become more skilled they progress from *freezing* to *freeing* tendencies. In the context of goal-directed actions, *freeing* means that the CNS allows the relevant joints to move through any of their respective degrees of freedom. The more recent interpretation of coordinative tendencies, however, suggests that a more skilled or developed performance is not always indicated by freeing as originally stated by Bernstein (Newell & Vaillancourt, 2001). Depending on the task demands, *freeing* or *freezing* may represent the optimal tendency (Newell & Vaillancourt, 2001). For instance, adults tend to *freeze* the wrist joint when performing pointing actions to keep a straight wrist path (Marraso, 1981), but they *free* the wrist when performing a one-handed catch (Mazyn et al., 2006). Also, adults may *free* one joint, but *freeze* another in order for the action to be functional. From a methodological perspective, the emerging coordination tendencies (*freezing/freeing*) can be inferred from the degree of association between the joints in the form of movement product (i.e., correlation coefficients) and process measures (i.e., angle-angle plots) (e.g., Mazyn et al., 2006).

Biomechanical constraints. Aside from soft constraints, hard constraints also play a role in the generation of functional actions. They can be either neuromuscular or biomechanical in nature. Depending on the level of coordination examined (i.e., intra-limb vs. inter-limb), the impact of biomechanical or neuromuscular constraints may be more or less pronounced. In intra-limb coordination, the former plays a more prominent role (Carson, Byblow, Goodman, & Swinnen, 1994; Carson, Riek, Smethurst, Parraga, & Byblow, 2000).

Bi-articular muscles. One particular biomechanical constraint that influences uni-manual movements is muscle articulation. Muscles can span either one or two joints. During multi-joint actions, mono-articular muscles create the majority of muscular force. On the other hand, bi-articular muscles also produce force, but their secondary role is to control the direction of the force applied by the individual muscles (van Ingen Schenau et al., 1987). A bi-articular muscle assists movement organization because it controls two different joints. For instance, when performing voluntary movements with the arm, the biceps brachii contributes to both shoulder and elbow flexion (Lacquaniti & Soechting, 1986). This anatomical structure is a biomechanical constraint on the emerging action because the biceps brachii activation could potentially force the shoulder and elbow to couple their angular displacement. Nevertheless, the presence of bi-articular muscles does not always assure tight coupling between joints, as evident from decoupling the elbow and wrist in pointing/reaching actions (Lacquaniti & Soechting, 1982).

Limb dynamics. Another biomechanical constraint that influences movement organization is the production of passive force. The magnitude of muscular force produced at one joint (e.g., elbow) is dependent on the passive force, or torque, produced by the other joints (e.g., shoulder and wrist) and the environment. There are different sources of passive torque and this torque can be due to gravitational force, centripetal/Coriolis force, and inertial properties of other segments (Hollerbach & Flash, 1982).

Gravitational force produces passive torque and it is most influential in coordination of slower movements that take place in the sagittal plane (Yamasaki, Tagami, Fujisawa, Hoshi, &

Nagasaki, 2008). As long as the action does not occur on a horizontal surface and the line between the axis of rotation and the center of mass of a segment is not parallel to the gravitational pull, a passive torque will be applied to the joint attached to that segment. This torque can be constant or constantly changing depending on the emerging movement pattern. It does not matter if the movement is static or dynamic, as the CNS must adapt the muscular torque to modulate/control gravitational torque during both types of actions (e.g. Yamasaki et al., 2008).

Since the majority of goal-directed actions are dynamic, other passive forces are present during multi-joint movements. Regardless of the presence of bi-articulate muscles, the acceleration of one segment and its inertial properties will affect the overall net torque of the other joints involved in the action (Hollerbach & Flash, 1982). For instance, due to acceleration of the shoulder joint and its moment of inertia, an additional torque can be translated to the elbow and the wrist. This torque is also known as inertial coupling force (Zatsiorsky, 2002). This force constrains action because it contributes to angular displacement of the other joints involved in the action. Hence, the CNS must adapt or regulate the magnitude of muscular torque at the joint that is affected by inertial coupling torque (Hollerbach & Flash, 1982).

The other two passive forces that are produced during multi-joint actions are centripetal and Coriolis force. While inertial coupling force is produced from acceleration, these forces are based on the velocity of a segment (Hollerbach & Flash, 1982). Centripetal force acts through the axis of rotation, while, depending on the other joints' direction of motion, the Coriolis force acts perpendicular to the end-point path. If one joint is stationary, these forces are not present. When all joints are in motion, however, the frame of reference becomes non-inertial and the centripetal and Coriolis forces affect joint rotations constituting an additional passive torque on the joints involved. In the past research, the term interactive torque was used to describe the combination of centripetal, Coriolis, and inertia coupling forces (Hollerbach & Flash, 1982). As evident, the nature of intra-limb coordination, or spatial relations, is constrained by the production of active (muscular) and passive forces at each joint involved in the action and these torques must be effectively modulated or utilized to stabilize/control an intended action (Hollerbach & Flash, 1982).

Methodologically, torque modulation tendencies can be inferred from inverse dynamics (e.g., Zatsiorsky, 2002). A direct model can also be used, but an inverse model is methodologically simpler than the former. To complete an inverse dynamics calculation, the kinematic data, along with anthropometric data, must be used to estimate the forces produced at the joints involved (e.g., Jensen, 1986; Zatsiorsky, 2002). Torque modulation tendencies can be examined further by using a number of methods (e.g., time profiles; scatter plots), but the pilot study (Chapter 3) introduces a novel method to analyze torque modulation.

From a motor control standpoint, there are two hypotheses regarding the role of torque modulation in movement organization (Dounskaia, 2010). One hypothesis suggests that to organize functional actions the CNS completes an inverse dynamics calculation to determine the required torques for a given configuration of the joints (Hollerbach, 1982). The problem with this hypothesis is that a very detailed model of the joints' underlying kinetics and kinematics is needed, making it complicated to adjust torque production when small perturbations are present (Dounskaia, 2010).

Another hypothesis is that optimal movement organization is marked by the ability to utilize passive torque at the distal joints due to acceleration/deceleration of the most proximal joint. For instance, in goal-directed actions (e.g., Galloway & Koshland, 2002; Gribble & Ostry, 1999), the shoulder produces a large muscular torque that would transfer an interactive torque to the elbow. The muscles that control the elbow joint would utilize the interactive force to assist in producing an effective action, meaning less active torque is required to move the elbow joint. This evidence is also consistent with Bernstein's (1967) original notion that optimal movement is marked by an individual utilizing the reactive phenomenon that arises from multiple joint interactions and the environment. Bernstein's idea was extended and further developed by Dounskaia (2005) and given the name *leading joint hypothesis*. According to this hypothesis, the leading joint's underlying dynamics are similar to a single-joint movement, as the majority of joint displacement is due to muscular torque and only partially depends on interactive torque. In most cases the more proximal joint (e.g., shoulder) is the leading joint because it moves through a large range of motion. When the leading joint is proximal, the more distal joints (e.g., elbow and wrist) are subordinate and modulate the passive torque from the leading joint to contribute to their own displacement.

Factors affecting torque modulation. Similar to how spatial relations emerge, the task also influences how torque is modulated. Evidence from the research carried out by Dounskaia and colleagues (2002), revealed that in continuous horizontal drawing actions, the proximal joint (i.e., shoulder) was the leading joint, while the distal joint (i.e., elbow) was subordinate. During one of the actions, the proximal and distal joints switched roles, as the distal joint became the leading joint and, due to limited range of motion, the proximal joint became subordinate. Differences in torque modulation can also be task and joint specific (Newell & Vaillancourt, 2001). During uni-manual actions in typically functioning adults, the wrist is known to move in a relatively straight path (Morasso, 1981). To produce this outcome, the muscles that control the wrist contract to perfectly oppose movement due to interactive force from the proximal joints (Koshland, Galloway, & Nevoret-Bell, 2000). This torque modulation strategy is optimal because it requires a small magnitude of muscle (active) force to produce the desired movement pattern, therefore making the movement energy efficient (Dounskaia, 2005). In cyclical elbow-wrist actions (Dounskaia, Swinnen, Walter, Spaepen, & Verschueren, 1998), however, the passive torque from the elbow was used to contribute to or counteract movement at the wrist depending on what type of action was being performed (i.e., bi-directional, uni-directional, or free-wrist pattern).

Although the task goal largely influences torque modulation, other task constraints impact the underlying dynamics. In fact, modulation of interactive torque is more influential in fast movements, while gravitational torque has a larger role in slower vertical actions (Yamasaki et al., 2008). For instance, throwing a fast-ball would rely largely on modulation of interactive torque (Hirashima, Kudo, Watarai, & Phtsuki, 2007), while catching a ball is a much slower movement, therefore, relatively speaking, torque modulation would rely more on gravitational torque. Thus, the literature shows that torque modulation is dependent on the nature of the task and the speed which is required to complete the action.

Typical and atypical torque modulation. Task constraints evidently impact the nature of torque modulation, but it is of importance to understand how populations differ in terms of modulating torque and how this difference affects the emerging action. The above examples describe optimal torque modulation at the intra-limb level, which has been inferred by examining adults. On the other hand, less than optimal torque modulation has been studied in populations that perform simple goal-directed actions ineffectively. These populations include, but are not limited to, infants (Dichgans & Konczak, 1997; Konczak, Borutta, Topka, & Dichgans, 1995; Jensen, Thelen, Ulrich, Schneider, & Zernicke, 1995; Schneider, Zernicke, Ulrich, Jensen, & Thelen, 1990; Zernicke & Schneider, 1993), elders (Ketcham, Dounskaia, & Stelmach, 2004), and persons with a neurological impairment (Bastian, Martin, Keating, & Thach, 1996; Bastian, Zackowski, & Thach, 2000; Dounskaia, Ketcham, Leis, & Stelmach, 2005; Ghez & Sainburg, 1995). No research has examined torque modulation strategies in older children performing uni-manual goal-directed actions. Developmentally, it is known that tasks requiring force/torque adaptations (e.g., catching, reaching) are adult-like by the age of 9-12 (e.g., Savelsburgh & van Santvoord, 1996). It remains unclear, however, when torque modulation becomes mature in voluntary movements, particularly those taking place under external time demands when speed is a primary task constraint.

When infants organize goal-directed reaching movements, the elbow joint precedes the motion of other joints in the limb (Konczak & Dichgans, 1997; Zernicke & Schneider, 1993) At the behavioural level of analysis, this sequence results in decoupling or segmentation. To move each joint independently, the passive force must be counteracted at the joint that is *frozen out* by utilizing the passive torque (Zernicke & Schneider, 1993). In early reaching, this tendency is not present and the result is a segmented movement pattern (Zernicke & Schneider, 1993).

Another consequence of less than optimal torque modulation is the lack of ability to utilize large magnitudes of interactive torque at the subordinate joint(s) (Bastian et al., 1996; Bastian et al., 2000). This tendency is problematic because the muscles are not able to control the passive torque. For example during a pointing task, adults with cerebellar lesions were required to keep the shoulder stationary, but the interactive torque from the elbow (i.e., leading joint) was ineffectively regulated (Bastian et al., 2000). At the behavioural level, this transfer of passive torque ultimately produced an excessive, ineffective *freeing* of the shoulder joint and an erroneous trajectory of the hand (Bastian, et al., 2000). Thus, *freezing* can be underlined by less than optimal torque modulation and ineffective *freeing* can be due to a different, less functional modulation of torques.

Chapter 2: Ball Catching and Coordination in Children with DCD

Children with DCD have coordination problems that could be one factor contributing to their lack of success when performing a given task. What has been found is that children with DCD have issues organizing actions during a number of tasks, and one of these tasks is ball catching (Wright & Sugden, 1996). One of the first studies to examine issues related to a variety of catching skills in children with DCD was completed by Van Waelvelde and colleagues (2004). In this study, a group of children with and without DCD attempted to catch a ball a number of ways (e.g., two vs. one-handed). It was found that the children with DCD, when compared to their age-matched peers, caught significantly fewer balls across the tasks. In addition, the children with DCD performed qualitatively different movement patterns when catching.

Recently, Utley and Astill (2007) provided a more detailed description of the emerging catching action in a two-handed task. These researchers studied the degree and stability of the two-handed catch by completing a behavioural analysis on preferred coordination patterns exhibited by children with and without DCD. Participants were required to catch a ball at the center of the body for 30 trials. Stability was inferred by how frequently a movement profile, or catching pattern, was exhibited across the trials. The results showed that the children with DCD exhibit different and more variable movement forms across trials, when compared to their age-matched peers. Ultimately, this result means children with DCD had difficulties organizing and producing a consistent action during two-handed catching. The researchers concluded that this group of children have yet to obtain an optimal catching pattern that can consistently achieve a task goal.

Limited research has examined the nature of coordinative tendencies in two-handed catching. Utley, Steenbergen, and Astill (2007) studied whether children with DCD froze or freed the elbow joint during a two handed catching task. Children with DCD had a smaller range of motion (~15 degrees) at the elbow joint compared to their typically functioning age-matched peers. This result showed that children with DCD froze out the elbow joint during the action and that this freezing potentially could lead to decoupling/segmentation of the emerging movement pattern, however, this issue was not explicitly examined in this research (Utley et al., 2007).

Przysucha (2011) studied the nature of bi-manual coordination in a small sample of children with DCD during a two-handed catching task. In addition to the primary analysis, intra-limb coordination was also examined. Children with DCD exhibited a universal decoupling tendency between the shoulder-elbow and elbow-wrist joints compared to typically developing peers. As evident from the angle-angle plots in Przysucha's research, this lower degree of coupling was indicative of segmentation. These spatial relations (i.e., shoulder-elbow, elbow-wrist) were also more variable across trials. This result means that the children with DCD produced qualitatively different and less stable movement patterns, as they coordinated the joints independently during the catch. The nature of intra-limb coordination, however, may be different in uni-manual catching since coordination (e.g., degree of coupling) is dependent on the task constraints (Newell, 1985).

Past studies, and other research, have studied issues related to movement functionality, coordination, and stability during two-handed catching in children with DCD (Astill 2006; Przysucha, 2011; Przysucha & Maraj, 2010; Utley et al., 2007; Utley & Astill, 2007; Van Waelvelde et al., 2004). Only limited research has examined one-handed catching in children with DCD, and no research has explicitly examined intra-limb coordination during this task. The first study to investigate one-handed catching in children with this disorder was completed by Estil, Ingvaldsen, and Whiting (2002), who examined the spatial and temporal characteristics of the end effector (i.e., hand). The children completed two tasks separately; one task evaluated the transport phase of the catch, while the other task examined the grasp. The results showed that children with DCD had more spatial errors compared to typically developing children. In addition, children with DCD exhibited more problems while grasping the ball. This research showed that children with DCD have problems with both the transporting and grasping during a one-handed catch.

A study completed by Deconinck and colleagues (2006) examined the grasp component of the one-handed catch. The task required the children to have their catching arm fixed on a table and to grasp a ball that was released from a pendulum. Reflective markers were attached to the index, thumb, and middle finger of the catching hand. There was no difference in the kinematics of grasping between the two groups of children, except the children with DCD exhibited a lower maximum hand closing velocity. In addition, there was no difference in the number of balls caught between groups. It is evident from this research (Deconinck et al., 2006) that children with DCD may not have issues grasping a ball. Once again, this study only examined end-effector organization and did not evaluate how the children coordinated their arm during the catch.

The existing literature examining one-handed catching in children with DCD is inconclusive. There were differences in spatial-temporal characteristics of the end-effector in some instances (Estil et al., 2002), but not others (Deconinck et al., 2006). Thus, it remains unclear which component of the catching action (i.e., joint organization vs. grasping) represents a problem. Also, corresponding coordinative issues have not been explicitly examined in an ecologically valid task (i.e., multiple degrees of freedom catch vs. restrained catch). Since populations with less than optimal torque modulation exhibit movement patterns similar to children with DCD (Cantin, Polatajko, Thach, & Jaglal, 2007), it is speculated that similar constraints at the kinetic level of analysis (i.e., lack of passive and active force modulation) underlie the problems children with DCD exhibit in intra-limb coordination, namely spatial coupling. For this reason, it has been difficult to delineate which constraints represent a limiter on how children with DCD solve the degrees of freedom problem in a one-handed catching task.

Purpose

The primary purpose of this thesis was to investigate the nature (degree; stability) and effectiveness of intra-limb coordination in boys with and without DCD during a one-handed catching task. The secondary purpose was to determine if the expected differences in intra-limb coordination coincided with differences in torque modulation at the shoulder, elbow, and wrist.

Research Questions

Are children with DCD able to perform a one-handed catching action with a similar level of success compared to typically developing children? Are there between group differences in the nature of intra-limb coordination (i.e., degree and stability) during a one-handed catching task? In addition, do these between group differences in intra-limb coordination coincide with differences in torque modulation across the relevant joints?

Hypothesis

It was hypothesized that, compared to typically developing children, children with DCD would perform less functional actions (Van Waelvelde et al., 2004). In addition, the children with DCD would exhibit weaker and less stable coupling across the respective joint pairs in relation to their typically developing peers (Przysucha, 2011). These differences would coincide with differences in torque modulation. More specifically, children with DCD were expected to utilize less passive and more active torque at the distal joints (i.e., elbow and wrist), as well as use less active and a similar amount of passive torque at the proximal joint (i.e., shoulder joint) (Bastian et al., 1996; Bastian et al., 2000; Dounskaia, 2010).

Chapter 3: Pilot Study

Biomechanical Constraints on Coordination in Children and Adults

Before the main study was completed, a pilot study was implemented for one of the dependent measures, namely torque modulation. This measure was based on Nikolai Bernstein's (1967) original hypothesis regarding optimal movement organization. Bernstein hypothesized that a person's movement repertoire has reached its full potential when he/she is able to use the reactive phenomenon that is produced by joint interactions. The notion of the *reactive phenomenon* is closely related to the process of modulating passive torque. The production of passive torque during a dynamic action is a biomechanical constraint that ultimately affects the nature of intra-limb coordination.

In addition, torque modulation tendencies are manifested at the behavioural level (e.g., Galloway & Koshland, 2002). This past research used time profiles to compare torque modulation to joint kinematics. Although it may be informative to examine the time profiles of torque production, this analysis would complicate the comparison of two different groups/populations needed for the main study for two reasons. First, the main study will involve children between 9 and 12 years of age. Because of potential anthropometric differences within the group, due to puberty, moment of inertia properties of the segments involved could be drastically different. This discrepancy in segment properties would create differences in the magnitude of torque produced at each joint. For example, if two children had the same net torque value at the shoulder, a child who weighs 40kg would have produced more torque in relation to himself as compared to a child who weighs 80kg. Second, time profiles are mostly used as descriptive statistics and it is difficult to use these profiles to determine between group differences using inferential statistics.

Other methods have also been used to examine torque modulation such as scatter plots (Koshland, Galloway, & Nevoret-Bell, 2000) or torque index (Dounskaia et al., 2002). In the latter, a ratio was used to exemplify how muscular torque contributed to net torque. This measure, however, could not distinguish the extent muscular torque was utilized when it resisted net torque. Although this aspect of torque modulation may not have been needed in the past research (Dounskaia et al., 2002), it could be necessary to understand how the coordination measures coincided with torque modulation for the present study. In this pilot study, correlation coefficients were used to describe how either muscular or passive torque is utilized to produce net torque at a joint. It is unknown whether or not this torque measure (i.e., correlation coefficients) is able to distinguish differences in intra-limb coordination. For this reason, this pilot study was used to validate this torque measure.

Pilot Study Purpose and Hypothesis

As a result, the purpose was to examine if torque modulation tendencies, as expressed by the novel measures (i.e., correlation coefficients), converged with expected qualitative differences between groups, as well as between different biomechanical structures (i.e., joint pairs).

Pilot Study Method

Participants and Procedures

Three children (*M* = 11 years, *SD* = 1) and three adults (*M* = 24.3 years, *SD* = 1.16) were recruited. Both males and females participated in the study. Purposive sampling was implemented. The adult participants were recruited from the School of Kinesiology at Lakehead University, while the children were recruited from the "Track and Field Basics" program at Lakehead University. Each participant completed a single testing session that was 45 minutes long, at Lakehead University C.J. Sanders Building, in room 1028. Before the testing session, the researcher determined hand dominance of the adults by asking them which hand they preferred for catching. Since some children did not know their dominant hand for catching, their writing hand was considered as their catching hand. The children and adults attempted to catch ten balls, ejected from a tennis ball machine, at 7 m/s. The consistency of the apparatus was determined by ejecting a ball at a circular target with a radius of 4 inches. In total, 60 trials were completed and the tennis ball successfully hit the target on 55 attempts (92%). The resulting consistency was deemed as satisfactory.

Kinematic Analysis

Prior to data collection, the area where the participant caught the ball was calibrated using a Vicon Motus program and a 32-point control object (tree). The approximate size of the calibration area was seven cubic meters. The calibration tree was set-up so that the x-axis ran parallel to the ball flight so that, along with the 3D analysis, 2D coordinates could be used for the torque calculations. A 3D analysis was necessary because it was unknown how the action would emerge due to the multiple degrees of freedom involved in the catching task. In order to carry out a three-dimensional analysis of the emerging action, two high-speed cameras were set-up on the dominant side of the participant. Constrained by the room dimensions, one camera was positioned 35 degrees anterior to the frontal plane, and the other one 30 degrees posterior to the frontal plane (Appendix A). This set-up was used because three-dimensional transformation of marker coordinates is most optimal when the cameras are between 60 and 120 degrees apart (Allard, Stokes, & Blanchi, 1995). The transformation was completed using a direct linear transformation (DLT). Each camera was 5.5m away from the center of the calibration tree. The data were collected at 100Hz. To ensure adequate reflection of the markers, 300W halogen lights were placed at the same height as the cameras.

Precision and accuracy. In addition, precision and accuracy was calculated. Precision refers to how much variability exists between data points across two digitized trials. To measure precision, one trial of a single participant was digitized twice (~90 frames). The root mean square error formula was used to determine the level of precision of the hip, shoulder, elbow, wrist, and hand markers between the two digitized videos (Przysucha, 2011).

$$RMSE = \sqrt{\sum(\chi_i - \chi_{ii})^2 / N} \qquad \text{Equation (1)}$$

Where, χ_i = first clip data point

χ_{ii} = second clip data point

N = total number of frames

Table 1

Precision of the digitized hip, shoulder, elbow, wrist, and hand markers, in x, y, and z planes, using RMSE (mm).

Marker	Hip			Shoulder			Elbow			Wrist			Hand		
Plane	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z
RMSE	1.4	4.3	4.0	0.8	0.8	2.0	1.4	1.1	4.2	2.4	3.7	6.6	2.5	4.2	7.6

To determine accuracy, the calibration tree was used. Accuracy refers to the extent a measurement represents the true value of what is being measured. The distance between the closest and furthest *bulb* of each branch was determined using a measuring tape. The Vicon

Motus program was able to determine the location of bulb on the tree in Cartesian coordinates (x, y, z); these data were used to determine the length of the branch calculated by the Vicon Motus program. The measurement calculated from the program was compared to the distance of the branch using the measuring tape. Once again, equation 1 was used (RMSE), where xi is the *branch length*, xii is the *true* length of the branch, and N is the number of branches. This formula was used to determine how much systematic error was created when capturing the movement. As a result of the calculations, it was determined that the RMSE was 1.88mm for the two cameras.

Data Acquisition

For the catching trials, reflective passive markers were attached to the greater trochanter, one inch below the acromion in line with the glenoid process, lateral epicondyle, styloid process of the ulna, and the distal end of the 5th metacarpal of the participant's dominant hand. The researcher also weighed each participant and measured the segment lengths of the dominant arm (upper arm, forearm, and hand) to approximate center of mass, location of the center of mass, and moment of inertia based on calculations by Jensen (1986). To approximate the anthropometric data of the adults, equations published by Zatsiorsky (2002) were used. To determine the upper arm length, the distance from the glenoid process to lateral epicondyle of the humerus was measured. The forearm length was determined by measuring the distance between the lateral epicondyle and the styloid process of the radius. Lastly, the length of the hand was determined by measuring the distance between the middle of the wrist in line with the styloid process of the ulna and the tip of the 3rd phalange. These measurements were subsequently used to estimate torque production through equations reported by Zatsiorsky (2002).

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \begin{bmatrix} I_{1,1} I_{1,2} I_{1,3} \\ I_{2,1} I_{2,2} I_{2,3} \\ I_{3,1} I_{3,2} I_{3,3} \end{bmatrix} \begin{bmatrix} \ddot{\alpha}_1 \\ \ddot{\alpha}_2 \\ \ddot{\alpha}_3 \end{bmatrix} + \begin{bmatrix} \nu(\alpha,\dot{\alpha})_1 \\ \nu(\alpha,\dot{\alpha})_2 \\ \nu(\alpha,\dot{\alpha})_3 \end{bmatrix} + \begin{bmatrix} G(\alpha)_1 \\ G(\alpha)_2 \\ G(\alpha)_3 \end{bmatrix}$$

Equation (2)

Where 1 = shoulder

2 = elbow

3 = wrist

T = muscular torque

I = moment of inertia

α = joint angle

$\dot{\alpha}$ = angular velocity

$\ddot{\alpha}$ = angular acceleration

G = gravity

In equation 2, the product of "I" followed by "1,1", "2,2", "3,3" and angular acceleration of the appropriate joint determined the net torque at the shoulder, elbow, and wrist, respectively. The product of "I" followed by "1,2", "1,3", "2,1", "2,3", "3,1", "3,2" multiplied by the appropriate angular acceleration, via matrix algebra, are the inertia torques (e.g., 1,2 is the torque at shoulder due to angular acceleration at the elbow). $\nu(\alpha,\dot{\alpha})$ is the centripetal and Coriolis forces, and G is gravitational torque. Expansion of the equations is provided in Appendix B.

The footage of the catching action was digitized using a Vicon Motus program (Allard, Capozzo, Lundberg, & Vaughan, 1998). To infer the beginning of the catching action, an infrared sensor was set-up at the mouth of the tennis ball machine's shaft. The sensor was attached to a circuit that was normally open and when the tennis ball broke the infrared beam, the circuit closed and turned on an LED light. This light was seen by both cameras, and was used to manually synchronize the video footage during the trimming process. After the trimming process was completed, two randomly selected trials were digitized to determine the cut-off frequency. This cut-off point was determined by taking the scaled 3D coordinates from each data point (i.e., shoulder maker) and transforming them from a time to a frequency domain. After this calculation, the frequency-amplitude graph was analyzed to determine the most dominant frequency. As a result of this procedure, a low pass Butterworth filter was set at 5Hz for each marker to filter out any noise due to digitizing error. In addition, there was excessive noise in the torque modulation data, so the torque data were also transferred from a time to frequency domain. This process determined another cut off frequency for the torque data. After this calculation, the researcher was able to manually apply a low pass Butterworth filter at 5 Hz based on Winter's equations (2008).

Dependent measures

Movement functionality was inferred from the percentage of balls caught across trials (number of catches / total number of attempts). The degree of coordination was examined using correlation coefficients between angular displacement of relevant joint pairs. To do so, passive reflective markers were needed to calculate angular displacement of the shoulder, elbow, and wrist. The shoulder angle was the angle between the hip, shoulder, and elbow marker. The elbow angle was determined by the angle between the shoulder, elbow, and wrist marker, while the wrist angle was calculated by the elbow, wrist, and hand marker. Joint angular displacement alone describes the range of motion of the joints (degrees) during the catching movement, whereas the correlation coefficients allow inferences regarding the degree of spatial coupling (coordination) between the joints. A high correlation was considered as close to ± 1 and a low correlation was near 0. A high correlation coefficient reflected *tight* coupling between the joints meaning that the two joints were continuously changing in relation to one another. A low correlation coefficient indicated decoupling between joints, in other words, the joints were not moving in relation to one another Also, angle-angle plots were used to infer the qualitative nature of the emerging action.

The last two measures were in regard to torque modulation. The inverse dynamics torque calculation was used to estimate the muscle, gravitational, inertial, centripetal, Coriolis, and net torque produced at the joints during the one-handed catch using the kinematic and anthropometric data. The torques examined for the analysis were net, muscular and passive (combination of gravitational and interaction torque). First, the relationship between net (NET) and muscular (MUS) torque was examined. To quantify this relationship, correlation coefficients were used. A high positive relationship indicated that primarily muscular torque was used to produce the net torque at a joint, while a high negative relationship indicated that muscular torque was used to counteract the net torque. Also, a low relationship indicated that minimal muscular torque was used. Correlation coefficients were also used to measure the utilization of passive (PAS) torque. Passive torque (Equation 2) was used because the catching action was slow and in the sagittal plane, thus gravity played a large role in the movement organization (Yamasaki et al., 2008). A high positive relationship indicated that the passive torque was used to contribute to the overall net torque and joint displacement, while a high negative relationship indicates the CNS used the passive torque to counteract the net torque at a particular joint. Also, a low relationship indicated that the CNS did not use passive torque to contribute to net torque. For instance, if the correlation coefficient between NET-PAS torque at the elbow joint is high and positive and the correlation between NET-MUS torque was low or negative, then it is speculated that the CNS utilized more passive torque at the elbow joint to produce the movement. If there are moderately positive correlation coefficients between NET-PAS and NET-MUS, this finding would indicate that both muscular and passive torque contributed to the net torque, at that particular joint.

Design and analysis

A 2 Group (children vs. adults) x 2 Joint Pairs (shoulder-elbow vs. elbow-wrist) mixed factorial design was used. Due to a small sample size, only descriptive statistics were incorporated. The degree of coordination was determined by the mean value across five trials. To measure intra-subject variability, or stability, each participant's standard deviation was calculated across the selected trials. Aside from the aggregated data for the coordination measures, only two individual profiles were used to describe the torque measures due to digitizing errors.

Results and Discussion

Movement functionality. The adult group as a whole caught 93% (28/30) of the balls across the trials showing that their movement patterns were effective. On the other hand, the children did not exhibit the same success rate as they only caught 43% (13/30) of the balls. This result indicated that the children in this sample did not perform the task with a high success rate as they caught less than 70% of the balls (Williams, 1992).

Spatial coordination. First the nature (degree and stability) of coordination was examined at the shoulder and elbow joints. This same analysis was carried out at the elbow and wrist joints.

Shoulder-elbow. The mean correlation coefficient between the shoulder and elbow for the adults (M = .85) was relatively high compared to the children (M = .57). In addition, the adults' shoulder-elbow coordination was very stable (*SD* = .07), as compared to the children (*SD* = .18). This result indicated that the adults exhibited tighter and more stable spatial relations between the shoulder and elbow joint compared to the children during the one-handed catching task. The nature of coordination, at the shoulder and elbow, exhibited by the adults in this study was consistent with previous work completed by Mazyn and colleagues (2006) (r~.77). They examined intra-limb coordination during a one-handed catch at a similar ball speed (8.6m/s). This result is also consistent with past research involving adults while pointing or reaching to different targets (Soechting & Lacquaniti, 1981). This high correlation coefficient indicates that the adults moved the shoulder and elbow joint in relation to one another to control the transport phase of the catch. The children, however, moved the joints more independently. In addition to weaker coupling, children also exhibited higher intra-subject variability. This result is in contrast to the work completed by Savelsbergh and van Santvoord (1996) as in their study the children were able to move their shoulder and elbow in unison to catch a ball one-handed. It could be inferred that the children in this sample may not have developed an effective movement pattern to catch a ball with one-hand. Overall, these results indicated that the adults exhibited different coordination tendencies compared to the children at the shoulder-elbow joint pair.

Elbow-wrist. Since the nature of spatial coupling is joint specific (Lacquaniti & Soechting, 1982; Soechting & Lacquaniti, 1981), the elbow and wrist joints were the other joint pair used to examine intra-limb coordination during the one-handed catch. Similar to the shoulder-elbow relations, the adults (*M* = .82) had high correlation coefficients between the elbow and wrist joints. With regard to intra-subject variability, the adults exhibited higher variability (*SD* = .20) at the elbow-wrist compared to the shoulder-elbow pair. The adults' correlation coefficients were also consistent with previous literature, as the participants in Mazyn and colleagues' study had similar correlations (r = .80). These correlations were also higher compared to past research studying intra-limb coordination during pointing/reaching (Lacquaniti & Soechting, 1982). The higher correlation coefficient could be due to the task constraints. On the other hand, children, in comparison to the adults, exhibited weaker coupling of the elbow and wrist joint (M = .61). In addition to low coupling, the children also had higher intra-subject variability compared to the adults (SD = .26). The children did not couple the elbow and wrist joints and instead, they attempted to coordinate each joint independently. As evident from the nature of spatial coupling, the adults showed different coordinative tendencies at the elbow-wrist compared to the children during the one-handed catching task.

Angle-angle plots. The adults exhibited tight coupling between the shoulder-elbow and elbow-wrist pair, as inferred from the magnitude of correlation coefficients. There was, however, one adult who presented similar correlation coefficients to a child participant across both joint pairs. Nevertheless, as evident from *Figure 2*, at the behavioural level, these two participants exhibited completely different movement patterns. For this reason, correlation coefficients and angle-angle plots were both needed to describe the nature of intra-limb coordination. The following discussion describes how similarities in correlation coefficients coincided with differences at the behavioural level.

In *Figure 2*, there were no between participant differences in shoulder-elbow coupling as indicated by the correlation coefficients (r = .75 vs. r = .74). At the behavioural level, there were noticeable differences. The adult participant performed the one-handed catch by flexing the elbow joint with minimal movement of the shoulder joint. In the second part of the movement, the shoulder began to flex with minimal movement of the elbow joint. This movement pattern was noticeably segmented. The child participant, also had a similar correlation coefficient, but the movement was performed differently. In this example, the shoulder begins the movement by flexing upwards toward the ball, while freezing the elbow joint. After this action, there was a slight change in elbow flexion, followed by an extension of the shoulder joint. This result exemplifies that, despite the similar correlation coefficients, the adult performed a qualitatively different movement pattern compared to the child. Therefore, there is a necessity to include both measures to describe the shoulder-elbow relations.

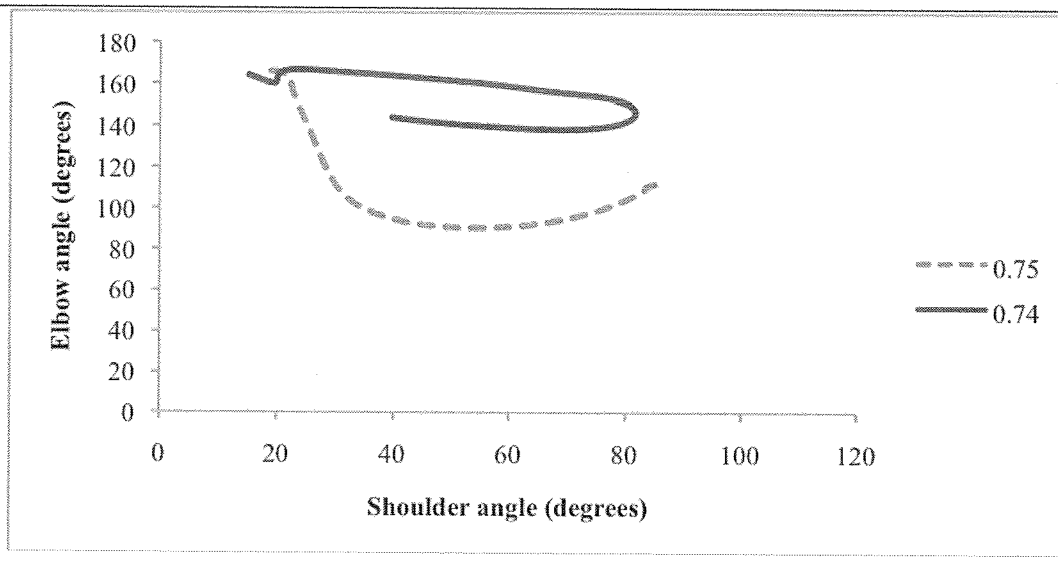

Figure 2. Angle-angle plots for the shoulder-elbow for the child (solid line) and adult (dotted line).

Next the elbow-wrist relations were examined. Once again, the correlation coefficients of the two participants were similar (r = .76 vs. r = .75). At the behavioural level, however, the movement patterns were very different. As seen in *Figure 3,* the adult performed the one-handed catch by moving the elbow joint first followed by slight flexion of the wrist. During the second part of the movement, the wrist began to flex, while the elbow was extending. The child had a similar correlation coefficient, but performed the action by freezing out the elbow joint for the first part of the movement, followed by making numerous flexion and extension actions of the wrist joint.

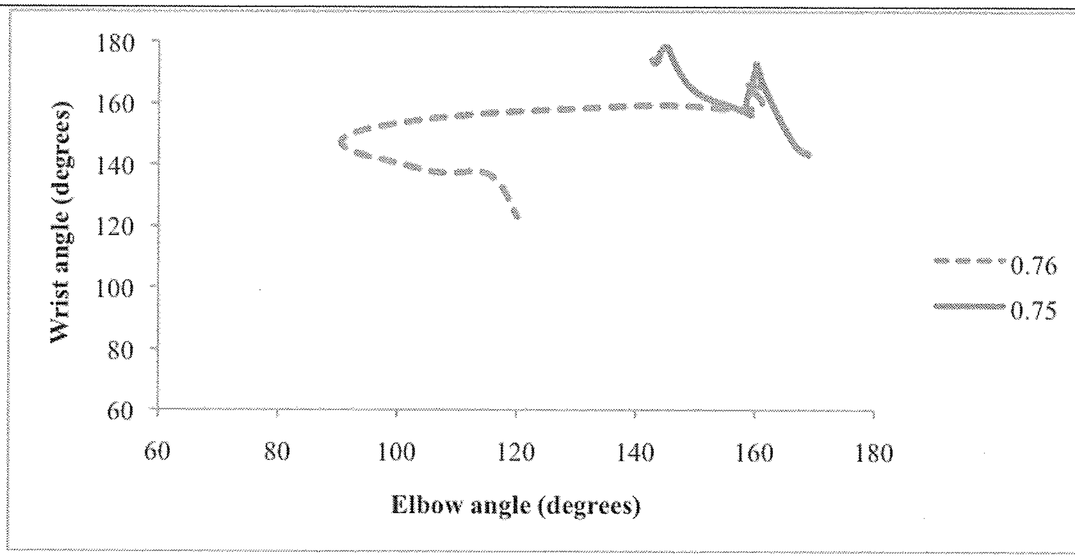

Figure 3. Angle-angle plots of the elbow and wrist joint for the child (solid line) and adult (dotted line).

As evident from the prior discussion, correlation coefficients alone do not always fully represent the quality of the emerging movement forms. The correlation coefficients of all the joint pairs were relatively equal (r = 0.74, 0.75, 0.75, 0.76), but the emerging patterns were drastically different. These results indicate that angle-angle plots and correlation coefficients are not redundant measures of coordination and both are needed to describe the true nature of intra-limb coordination.

Torque modulation. Accurate torque measures could not be calculated for two adults and two children because of digitizing error that could not be filtered out. For this reason, only the results of one adult and one child participant were analyzed to determine differences in torque modulation. This analysis aimed at determining if the torque measures could discriminate the expected qualitative differences between the two participants.

Adult participant shoulder-elbow. The adult used for this analysis performed the catching action with tight coupling at the shoulder-elbow joint (r = -.96). The degree of spatial coupling was considered optimal because the participant caught 100% of the balls. First the

NET-PAS torque relationship (*Figure 4*, top left and right) at both the shoulder and elbow joint was used to determine how it coincided with shoulder-elbow spatial relations, followed by the same analysis for NET-MUS torque relationship (*Figure 4*, bottom left and right). In regard to NET-PAS torque, the adult participant utilized minimal passive torque at the shoulder joint as evident from the low correlation coefficient (*Figure 4,* top left). Since the relationship between these torques was negative, it indicated that the shoulder had to oppose/counteract the passive torque to effectively modulate the net torque to allow for the joint movement. When examining passive torque modulation at the elbow joint (*Figure 4*, top right), it was evident that more passive torque was utilized at this joint compared to the shoulder joint. This NET-PAS torque relationship at the elbow provides evidence that the adult utilized passive torque to contribute/produce the net torque, and hence angular joint displacement, at the elbow.

This result is consistent with the leading-joint hypothesis (Dounskaia, 2005) and past research examining shoulder-elbow relations (Dounskaia et al., 2002), as the elbow joint was the subordinate joint and its angular displacement was produced by utilizing passive torque. This NET-PAS relationship at the elbow joint also coincided with tight coupling between the shoulder and elbow joint. Thus, it could be postulated that the shoulder and elbow joints formed this strong spatial relationship because the elbow joint coupled its net torque, and hence movement, with the shoulder joint's passive torque.

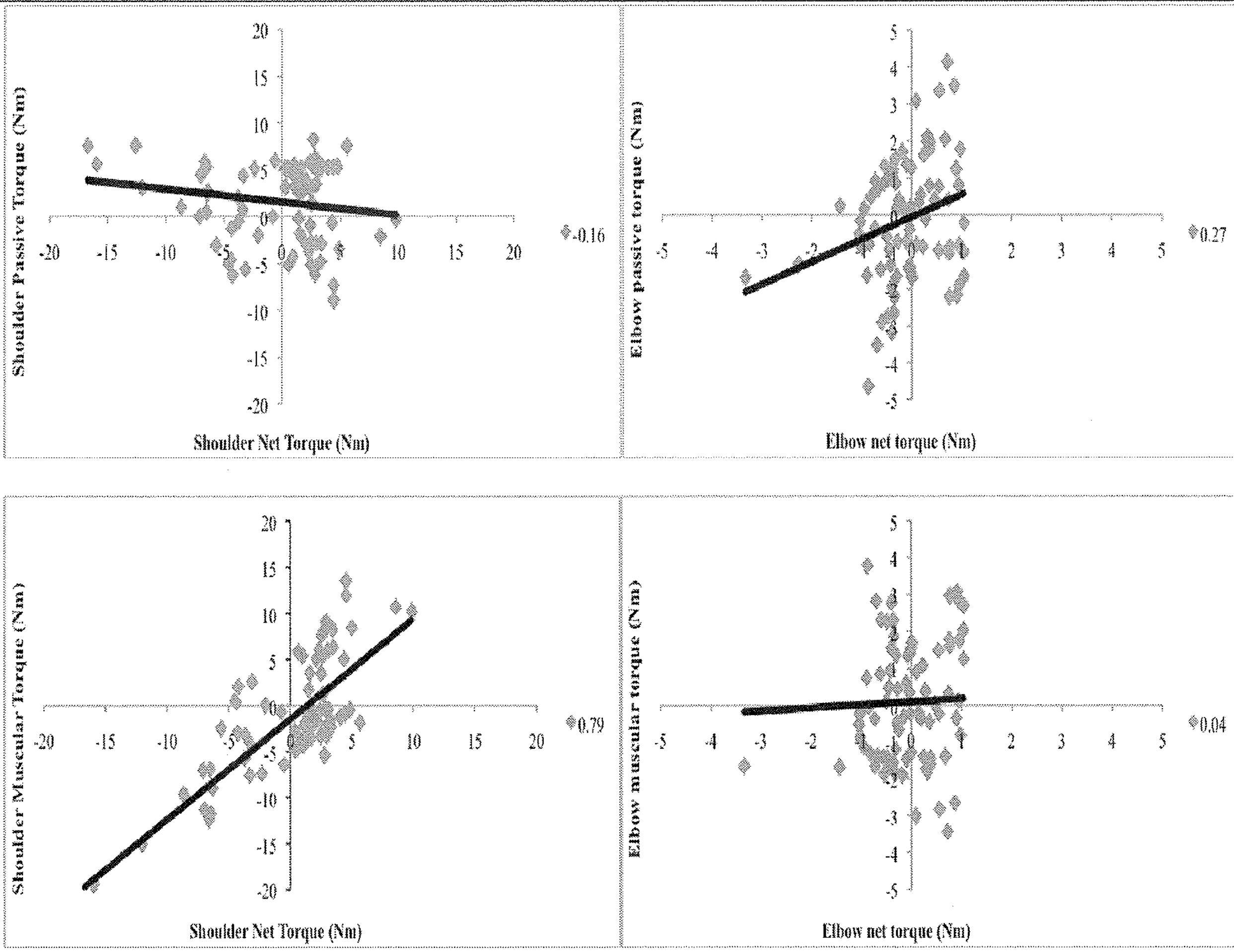

Figure 4. The relationship between torques at the shoulder and elbow for the adult participant. The top graphs are the scatter plots of NET-PAS torque modulation at the shoulder (left) and elbow (right) joint. The bottom graphs are the scatter plots for NET-MUS at the shoulder (left) and elbow (right).

The other measure used to examine torque modulation across the shoulder and elbow joints was the relationship between NET-MUS torque. As seen in *Figure 4* (bottom left graph), the adult participant presented a strong positive relationship between NET-MUS torque at the shoulder joint. This relationship indicated that the adult used primarily muscular torque to contribute to the overall net torque at the shoulder. This result was also consistent with the leading-joint hypothesis because the leading joint's (or shoulder) kinetics were similar to single-joint movement, as the majority of active torque contributed to net torque at the shoulder. In addition, the present results were in line with Galloway and Koshland (2002), who also reported that the net torque at the shoulder joint was primarily due to muscular torque during a pointing task.

Opposite to the shoulder joint, the adult participant had a very small or no relationship between NET-MUS torque at the elbow (*Figure 4*, bottom right). In this task, it is speculated that the adult participant used minimal muscular torque at the elbow joint because he was relying on passive torque to move the elbow joint. This result confirms that the tight shoulder-elbow coupling coincided with more utilization of passive torque, compared to muscular torque, at the elbow joint.

Child participant shoulder-elbow. The child decoupled the shoulder and elbow joint because as the elbow was moving the shoulder was not and vice versa (r = -.68). It was expected that the qualitative differences would coincide with different torque modulation. The data confirmed this hypothesis. As seen in *Figure 5*, the child performed that action by forming a weak relationship between net and passive torque at both the shoulder (top left) and elbow (top right) joints. This result means that the child utilized minimal passive torque to contribute to the overall net torque at the both joints.

The next measure used to examine the underlying kinetics was the NET-MUS torque measure. As evident from *Figure 5* (bottom left), there was a strong positive relationship between NET-MUS torque at the shoulder joint, indicating that the shoulder joint movement was due primarily to muscular torque. This finding was consistent with the predictions of the leading joint hypothesis (Dounskaia, 2005) because the majority of net torque was attributed to muscular torque and hence, the shoulder joint (or leading joint) acted like a single-joint movement. The one interesting result is that there was also a moderate positive relationship between NET-MUS at the elbow joint (*Figure 5*, bottom right). The magnitude of this relationship showed that the child attempted to utilize primarily muscular torque to move both the shoulder and the elbow joints. It is postulated that the child utilized muscular torque in this manner to control each joint independently, which coincides with the kinematic data (i.e., decoupling).

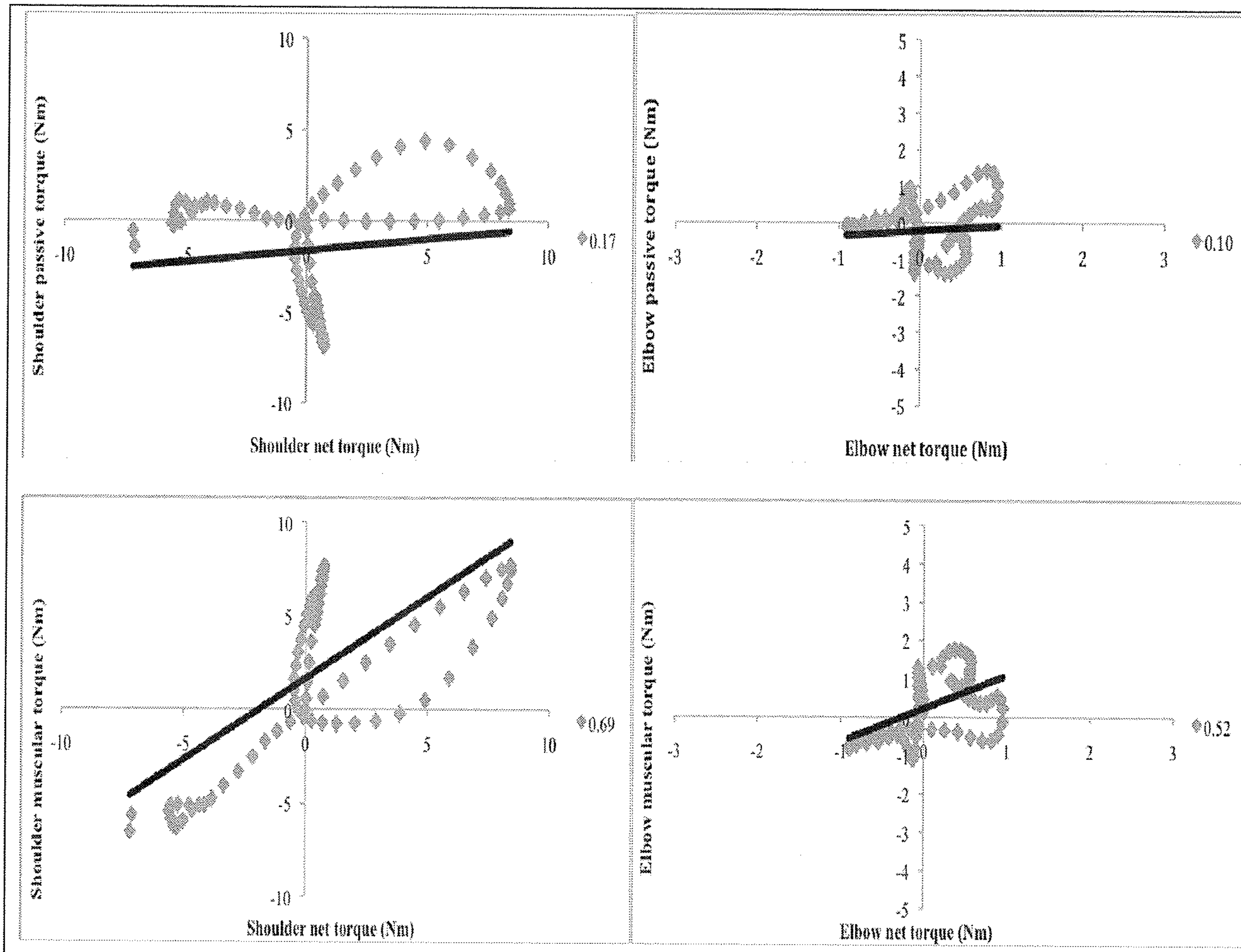

Figure 5. The relationship between torques at the shoulder and elbow for the child participant. The top graphs are the scatter plots of NET-PAS torque modulation at the shoulder (left) and elbow (right) joint. The bottom graphs are the scatter plots for NET-MUS torque at the shoulder (left) and elbow (right).

Adult participant elbow-wrist. The next joint pair that was used to analyze how torque modulation coincided with certain spatial relations was the elbow-wrist joint pair. The adult exhibited strong coupling between the elbow and wrist action, as indicated by the high correlation coefficient (r = -.93). The first torque measure used for this analysis was NET-PAS torque (*Figure 6*, top left and right), followed by the NET-MUS torque relationship (*Figure 6*, bottom left and right). In terms of NET-PAS torque, the elbow joint utilized passive torque from the shoulder (*Figure 6*, top left) and as discussed earlier, this was necessary for the coupling of the shoulder-elbow. The wrist joint also utilized passive torque to contribute to the net torque, as indicated by a moderately high positive correlation coefficient (*Figure 6*, top right). Once again, the more distal joint (i.e., wrist) in the pairing was subordinate because its movement was likely due to passive torque from the shoulder and elbow joints' torque. This result indicates that, like the shoulder-elbow pairing, tight coupling between the elbow-wrist coincided with utilizing passive torque at the distal joint (i.e., the wrist). It is unclear, however, if the adult utilized more passive torque in relation to muscular torque at this distal joint. For this reason, the relationship between NET-MUS torque at the elbow and wrist was also analyzed.

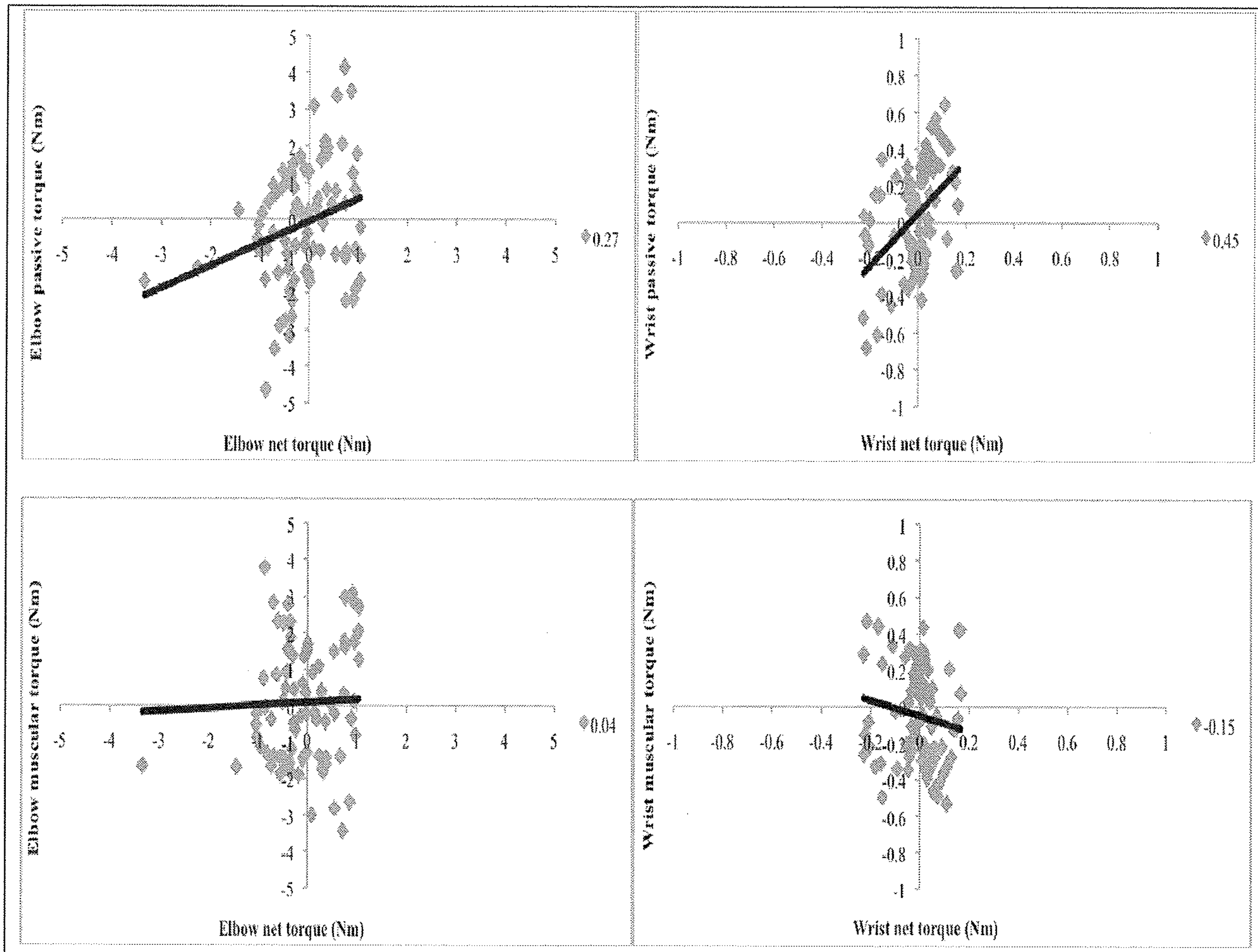

Figure 6. The relationship between torques at the elbow and wrist for the adult participant. The top graphs are the scatter plots of NET-PAS torque modulation at the elbow (left) and wrist (right) joint. The bottom graphs are the scatter plots for NET-MUS torque at the elbow (left) and wrist (right).

As *Figure 6* (bottom left) shows, minimal muscular torque was utilized to move the elbow joint. Unlike the shoulder-elbow relations, the distal joint (i.e., the wrist) had a weak negative relationship between net and muscular torque (*Figure 6*, bottom right). This correlation coefficient indicates that the muscular torque was utilized to potentially counteract or dampen the net torque at the wrist (Dounskaia, 2010). This result was consistent with past research by Galloway and Koshland (2002), as muscular torque was used to regulate the passive torque at the wrist to contribute to the appropriate net torque for the task. Overall, tight coupling between the elbow and the wrist coincided with more utilization of passive, as compared to muscular torque, at the distal joint (i.e., the wrist).

Child participant elbow-wrist. The child participant demonstrated similar coupling at the elbow and wrist joint (r = .94) compared to the adult, however, in a different direction (i.e., positive), indicating that the child and adult's movement patterns were qualitatively different. Consistent with the hypothesis, this difference in direction was expected to correspond with noticeable torque modulation differences at the elbow and wrist joint. The data confirmed this hypothesis. The NET-PAS torque measure revealed that there was a weak relationship between these torques at both the elbow and wrist joints (*Figure 7*, top right and left). In other words, passive torque was not primarily used at either the elbow or wrist to contribute to the net torque at each respective joint. The NET-MUS torque relations, however, revealed more information regarding torque modulation tendencies. As seen in *Figure 7* (bottom left and right), the child used primarily muscular torque at the elbow joint, but muscular torque was utilized minimally to contribute to the net torque at the wrist joint. This torque modulation tendency indicates that the child may be using a combination of muscular and passive torque to contribute to the joint movement. This torque modulation tendency coincided with tight coupling of the elbow and wrist joint in the positive direction. Since the movement pattern was different (i.e., child vs. adult), passive torque was utilized in a different manner. This result is consistent with research by Dounskaia and colleagues (1998), who showed that the torque modulation tendencies were dependent on the type of coordination pattern between the elbow and the wrist.

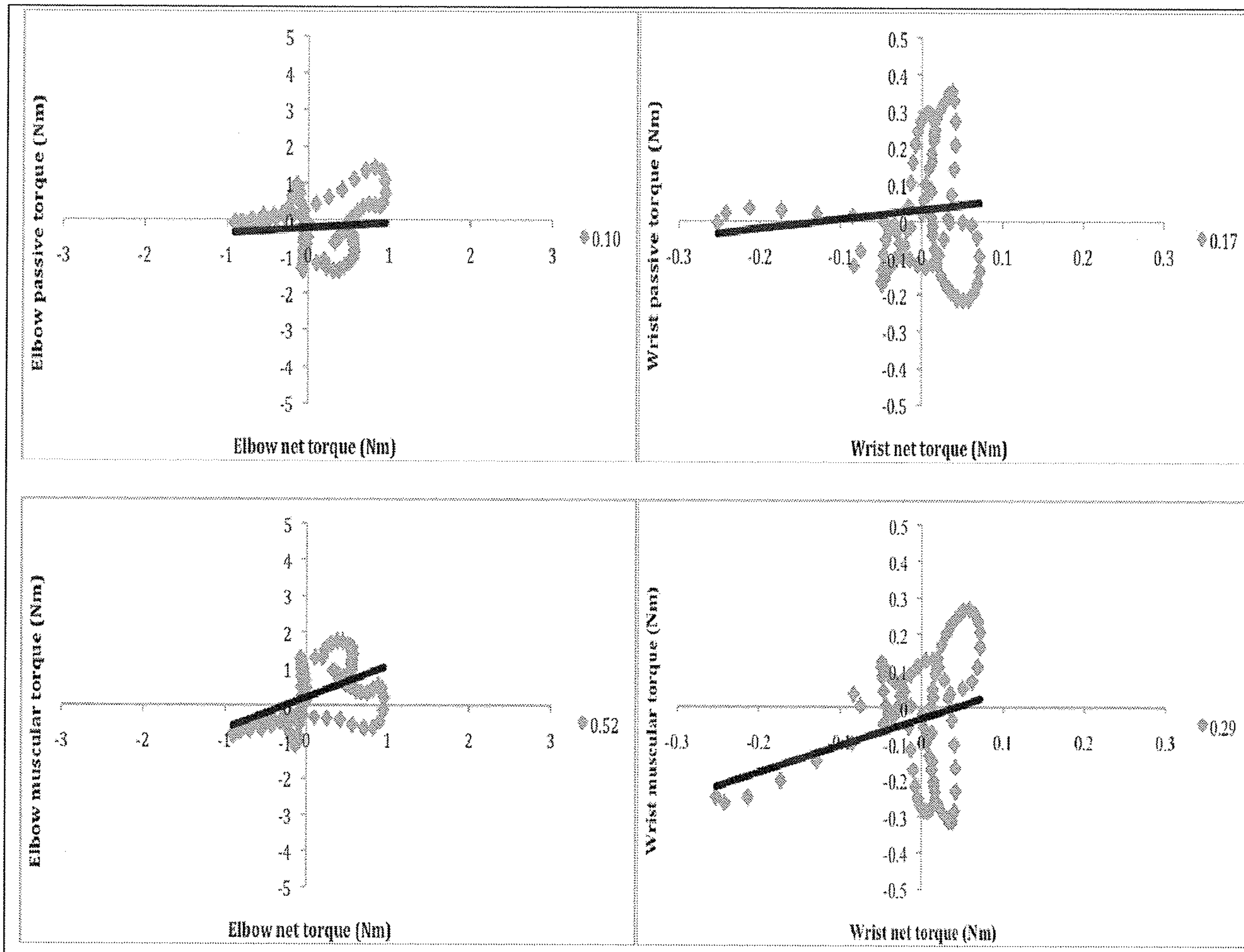

Figure 7. The relationship between torques at the elbow and wrist for the child participant. The top graphs are the scatter plots of NET-PAS torque modulation at the elbow (left) and wrist (right) joint. The bottom graphs are the scatter plots for NET-MUS torque at the elbow (left) and wrist (right).

Conclusion

The purpose of this study was to determine if qualitative differences would coincide with differences in torque modulation. The data showed that in fact the torque modulation measures used in this pilot study were able to distinguish differences in coordination at both the shoulder-elbow and elbow-wrist joint pairs. While catching the ball, the adult coupled the shoulder and elbow joint. This tight coupling coincided with utilizing primarily muscular torque at the shoulder joint, while utilizing more passive than active torque at the elbow joint. This torque modulation tendency is consistent with the leading joint hypothesis (Dounskaia, 2005), as the more proximal joint (i.e., the shoulder) was the leading joint, while the distal joint (i.e., the elbow) was subordinate. The child, on the other hand, decoupled the shoulder-elbow joints to catch the ball. Similar to the adult, the child utilized primarily muscular torque at the shoulder joint. Between participant differences emerged at the elbow joint as the child utilized more muscular and less passive torque at this joint to contribute to the net torque. This result shows that utilizing less passive torque, compared to muscular torque, at the elbow coincided with decoupling the shoulder-elbow joints. This result is consistent with the developmental research on torque modulation in infants (Jensen, et al., 1995), as the infants did not utilize passive torque at the elbow, which resulted in decoupling the shoulder-elbow pair.

In terms of elbow-wrist coupling, the child and adult exhibited tight coupling of these joints except in a qualitatively different way. The adult's catching action was performed with a strong negative relationship between the elbow and wrist joints, while the child had a strong positive relationship. As expected, the differences in coordination corresponded to differences in underlying kinetics. To sum up these differences, the child participant utilized primarily muscular torque at the elbow, while using both muscular and passive torque at the wrist joint. The adult participant, however, utilized more passive torque, compared to active torque, at the wrist joint. The adult's and child's performance was consistent with Dounskaia and colleagues' study (1998) as the nature of passive torque utilization at the wrist joint was dependent on the coordination pattern.

From a measurement standpoint, a few conclusions can be inferred. Tight coupling of the joints in the negative direction corresponded with utilizing substantially more passive torque than muscular torque at the distal joint in the particular pairing. The same degree of coupling in the positive direction, however, coincided with utilizing passive and muscular torque in a similar manner at the distal or subordinate joint (i.e., both active and passive torque were contributing to the net torque). Lastly, decoupling the joints corresponded to utilizing more muscular torque in relation to passive torque at the distal joint in the pair. It is apparent that the degree of coupling was dependent on how passive and active torque is utilized in relation to one another. This notion gives evidence that the torque modulation measures do not provide redundant information and both are needed to distinguish differences in coordination. Since there was convergence between the torque modulation (NET-PAS and NET-MUS) and coordination measures, it is evident that the novel torque measures are valid for describing the underlying kinetics across the relevant joints during a one-handed catching task.

Chapter 4: Main Study

It was evident from the pilot study that the novel torque modulation measures were suitable for distinguishing differences in coordination. It was necessary to validate these measures before studying the nature of coordination and underlying dynamics in children with and without DCD during a one-handed catching task. Given that the initial conditions before performing the task were the same, each child was presented with the same redundant number of degrees of freedom to perform the task. The following analysis and discussion determined how both groups of children solved the degrees of freedom problem and whether or not these potential between group differences were attributed to biomechanical constraints (i.e., joint involved; torque modulation).

Method

Participants and Recruitment Process

Nine typically developing boys (*M* = 10.6 years, *SD* = 1.08) and ten boys with DCD (*M* = 11.0 years, *SD* = 1.16) of the same age range were recruited. Purposive sampling was implemented. The typically functioning children were recruited from the Terrace Bay Public School. The researcher asked permission to recruit the children from the director of education, and the principal of the school involved (Appendix C). Once permission was granted, the researcher attended Terrace Bay Public School and gave a brief overview of the study during a scheduled class time to all of the boys that were in grades five, six, and seven. All the boys between the ages of 9 and 12 were given a recruitment letter (Appendix D), consent form (Appendix E), Developmental Coordination Disorder Questionnaire (DCDQ) (Appendix F), and child Par-Q (Appendix G) to take home to their parents/guardians to fill out. The children returned the forms to the teacher, and the principal contacted the researcher regarding who was interested in participating in the study.

The boys with DCD were recruited with the help of Dr. Jane Taylor. She is the coordinator of the motor development clinic at Lakehead University. The researcher gave Dr. Taylor the selection criteria for the study to determine which children to recruit. Dr. Taylor then contacted parents of the children who were previously in the clinic and asked if they were interested in participating in the research study. If the parents were interested, they contacted the researcher to arrange a meeting regarding the details of the study. At the meeting, the parents received a brief overview of the study and the recruitment letter (Appendix H). If the parents were still interested, they completed the consent form (Appendix I), DCDQ (Appendix F), and child Par-Q (Appendix G).

After consent was received from the parents, the researcher provided the parents with dates and times for testing, which took place in the multipurpose room (SB-1028) at Lakehead University. For the children who were recruited from the schools, the researcher set up a time with the teachers and principal to complete the sessions at their school in the gymnasium.

For the children to be included in the DCD group, they must have been males between the ages of 9 and 12, who met the four criteria based on the DSM-IV (APA, 2000). First, the coordination problems of the children with DCD must have been substantially lower compared to their age-matched peers. The level of movement proficiency was inferred from the Total Impairment Score (TIS) on the Movement Assessment Battery for Children (Henderson & Sugden, 1992). To be included in the DCD group, the children had to score below the 5th percentile for TIS. Second, the coordination problems they exhibited had to interfere with academic achievement and/or activities of daily living. To assess this criterion, parents completed the DCDQ and a score below 57, indicated there was interference in academic achievement due to movement difficulties. According to the third criterion, the children could not have any known medical condition (excluding ADHD). This criterion was inferred from the parents' responses on the consent form (Appendix E and I). Since children were recruited from the motor development clinic, their developmental history ruled out any of the children who had a medical condition interfering with their coordination. Lastly, the children must have had an Intelligence Quotient (IQ) above 85, as inferred from the parents' response on the consent form. The children recruited for this study were not formally diagnosed with DCD, as only a paediatrician can do so. Clinically, however, they met the specific research criteria for DCD as indicated by Geuze, Jongmans, Schoemaker, and Smits-Engelsman (2001). If a child had already been formally diagnosed with DCD by a paediatrician, he still completed the same assessment process as the other children.

The typically developing children were included in the study if they were males between the ages of 9 and 12 who scored at or above the 20th percentile for TIS (see Procedures of MABC testing). The children must also have had a score above 57, as a result of the DCDQ, and no known medical condition. Also to be included, the children must have had an IQ above 85.

The analysis of MABC scores showed that children with DCD were below the 5th percentile for TIS score (M = 1.1 %ile, SD = 0.31) and the children without DCD (M = 61.3 %ile, SD = 25.53) were above the 20th percentile for TIS. Individual data (Appendix J) confirmed the groups results. The children with DCD also met the inclusion criteria for the DCDQ as, on average, they scored below 57 (M = 44.2, SD = 16.7). Children without DCD also met the criteria by scoring, on average, above 57 (M = 61.8, SD = 7.21). Lastly, every parent/guardian of each typically developing child, indicated that his/her respective child met the inclusion criteria of "no known medical condition" and typical IQ (above 85). All of the children in the DCD group met the last two criteria because only clinic participants who met these criteria were recruited. All of the individual results are provided in Appendix J.

Procedures

Participants completed two testing sessions. The sessions took place during school hours for the children recruited from the Terrace Bay Public school, and after school at Lakehead University for the children with DCD. The first session took approximately 45 minutes, where the MABC was administered (Henderson & Sugden, 1992).

The catching session took place at Lakehead University C.J. Sanders Building or the gymnasium of the Terrace Bay Public school. Each participant completed the task individually. Prior to the start of the session, the researcher gave a brief verbal overview of what was required along with a demonstration of the task. During the practice trials, the researcher asked the participant to stand in front of the tennis ball machine, approximately 8 m away. The researcher adjusted the distance from the tennis ball machine so that, if the participant did not catch the ball then it would contact the dominant shoulder. The hand used to complete relevant tasks in the MABC was considered dominant. The starting position for the children was the same as the Pilot Study. While the participant was in his adjusted position, the researcher said "ready", and a tennis ball machine ejected a ball. Ten trials were carried out in total, with the ball travelling at 7 m/s. The participants were allowed five practice trials.

Since the torque calculations assume that the movements are planar, Equation 1 was used to determine differences in 2D and 3D coordinates collected from the Vicon Motus program (where *xi* was the 3D segment length, *xii* was the 2D segment length, and *N* was the total number of frames). The 3D scaled coordinates were taken from the Vicon Motus program and the z axis (i.e., linear displacement in the medio-lateral direction in relation to the participant) was removed. Using Microsoft Excel, the 2D segment length was then calculated across the entire trial. The 2D segment lengths (trunk, upper arm, forearm, and hand) were then compared to the respective 3D segment lengths using Equation 1. The logic behind this analysis is that if there are limited differences in the 2D vs. 3D segment lengths, there will be limited differences in angular displacement (2D vs. 3D). Hence, the torque equations would remain valid. As evident (Appendix K), the RMSE was small (<2cm) for 18 of the participants. For the remaining participant there were errors in the data extracted from Vicon Motus. Using Microsoft excel, appropriate corrections were made on the 3D scaled coordinates of this participant before calculating the dependent measures so that his results could be included in the analysis. This analysis confirmed that there were minimal differences in 2D and 3D coordinates, meaning the catching action was in fact planar for all participants and the torque calculations were applicable. A similar method was used by Bastian and colleagues (2000), as the segment length must not have changed more than 10% of its original length during the action. For instance, if the upper arm was 30cm, it must have remained between 27 and 33cm, as determined by the 2D analysis, throughout the entire action. The remaining aspects of the method section (i.e., Kinematic Analysis; Dependent Measures) are consistent with the pilot study.

Design and Analysis

A 2 Group (typically developing children vs. children with DCD) x 2 Joint Pairs (shoulder-elbow, elbow-wrist) mixed factorial design was used. To answer the first research question (i.e., movement functionality), an independent samples *t*-test was used to determine between group differences in the number of balls caught. To answer the second research question (i.e., nature of coordination), a series of 2 x 2 mixed factorial ANOVAs with repeated measures on the second factor were used to examine the dependent kinematic variables (i.e., degree and stability of coordination). For each individual, the mean value across trials 2, 4, 6, 8, and 10 was used for statistical analysis. To measure intra-subject variability, each participant's standard deviation was calculated across the selected trials. Lastly, angle-angle plots were used to further describe the nature of the emerging movement form.

To answer the third research question (i.e., torque modulation), a 2 Group (typically developing children vs. children with DCD) x 3 Joint (shoulder, elbow, wrist) mixed factorial ANOVA, with repeated measures on the second factor was used to examine potential differences in torque modulation for both NET-PAS and NET-MUS correlation coefficients. When necessary, individual torque profiles (i.e., NET-PAS; NET-MUS) were paired alongside angle-angle plots to determine if there was correspondence between coordination and underlying dynamics.

If a significant interaction effect was found for the dependent variables with the 2 x 2 ANOVA, planned comparisons were calculated. Independent samples *t*-tests determined between group differences and dependent samples *t*-tests determined within group differences. If a significant interaction effect was found for the dependent variables in the 2 x 3 ANOVA, independent samples *t*-tests determined between group differences, while a one-way ANOVA, followed by dependent samples *t*-tests were used to disentangle within group differences. To determine the effect size, eta square was calculated for each ANOVA. A value below 0.03 indicated a small effect, between 0.06 and 0.09 indicated a medium effect, and any value above 0.15 represented a large effect size (Cohen, 1977). Also, Cohen's d was incorporated to determine the meaningfulness of the differences emerging from the independent and dependent samples *t*-tests. A value below 0.2 was indicative of a small effect, approximately 0.5 was considered a medium effect, and any value above 0.8 was a large effect size (Cohen, 1977). In addition to the aggregated data, individual profiles were also described (Appendix J).

Results

The results section only contains information regarding the aggregate analysis. When necessary, the F or t statistic, significance level, and effect size were reported. Since DCD is a heterogeneous disorder, individual profiles of participants were also examined when appropriate.

Movement Functionality

Children without DCD ($M = 85\%$, $SD = 9.7$) on average caught significantly more balls in comparison to children with DCD ($M = 32\%$, $SD = 25.3$). Even though there was high within group variance, the independent samples t-test revealed that the children without DCD caught significantly more balls than the children with DCD ($t(17) = 6.18, p < .05, d = 1.61$).

Intra-limb coordination

Spatial relations. To examine the nature of coordination a 2 (Group) x 2 (Joint Pair) mixed factorial ANOVA with repeated measures on the second factor was completed. The dependent variable was the coefficient of the correlation between angular displacement of the shoulder-elbow and elbow-wrist joints. Each individual's mean correlation coefficient was used to evaluate the degree of coordination among relevant joints, whereas the stability of coordination was determined by using each individual's standard deviation across five trials.

Degree of coordination. In terms of the degree of coordination, a significant interaction effect ($F(1,17) = 10.78, p < .01, \eta^2 = .39$) was found (*Figure 8*). To determine potential between group differences, two independent samples t-tests were used. The t-tests showed that there were significant differences at the shoulder-elbow ($t(17) = 2.15, p < .05, d = .90$) and elbow-wrist ($t(17) = 2.44, p < .05, d = .99$) pairing. The children with DCD exhibited higher mean correlation coefficients for the shoulder-elbow pairing, but not for the elbow-wrist joint pair, where typically developing children had a higher mean correlation coefficient. To determine within group differences, two dependent samples *t*-tests were used. For the DCD group, there were significant differences between the shoulder-elbow and elbow-wrist ($t(9) = 2.52, p < .05, d = .80$). For the typically developing group, the differences approached significance ($t(8) = 2.14, p = .06, d = .71$).

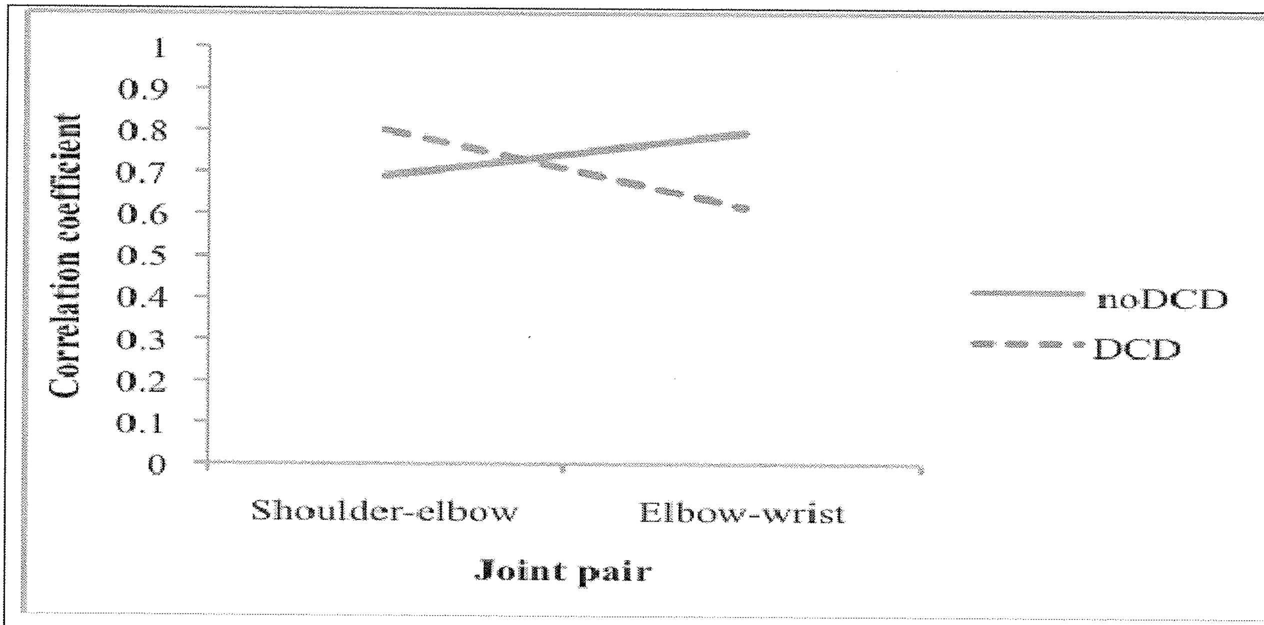

Figure 8. The degree of coordination across the shoulder-elbow and elbow wrist for both groups. The solid line represents the typically developing children (noDCD), while the dotted line depicts the children with DCD (DCD).

Stability of coordination. In terms of stability, a significant group main effect ($F(1,17) = 12.28, p < .01, \eta^2 = .42$) was evident. The children without DCD presented lower standard deviations compared to the children with DCD across the shoulder-elbow ($M_{dcd} = .12$ vs. $M_{w/odcd} = .09$) and elbow-wrist ($M_{dcd} = .21$ vs. $M_{w/odcd} = .09$) pairing.

Torque modulation

To determine differences in torque modulation a 2 (Group) x 3 (Joint) mixed factorial ANOVA with repeated measures on the second factor was used. The dependent variables were the correlation coefficients of net-passive and net-muscular torque.

Net and passive torque. A significant group main effect ($F(1,17) = 7.29$, $p < .05$, $\eta^2 = .30$) was found for passive torque utilization across the relevant joints. After examining the means (*Figure 9*), it was evident that the typically developing children had higher correlation coefficients between net and passive torque across all joints. In terms of stability, there were no significant differences found.

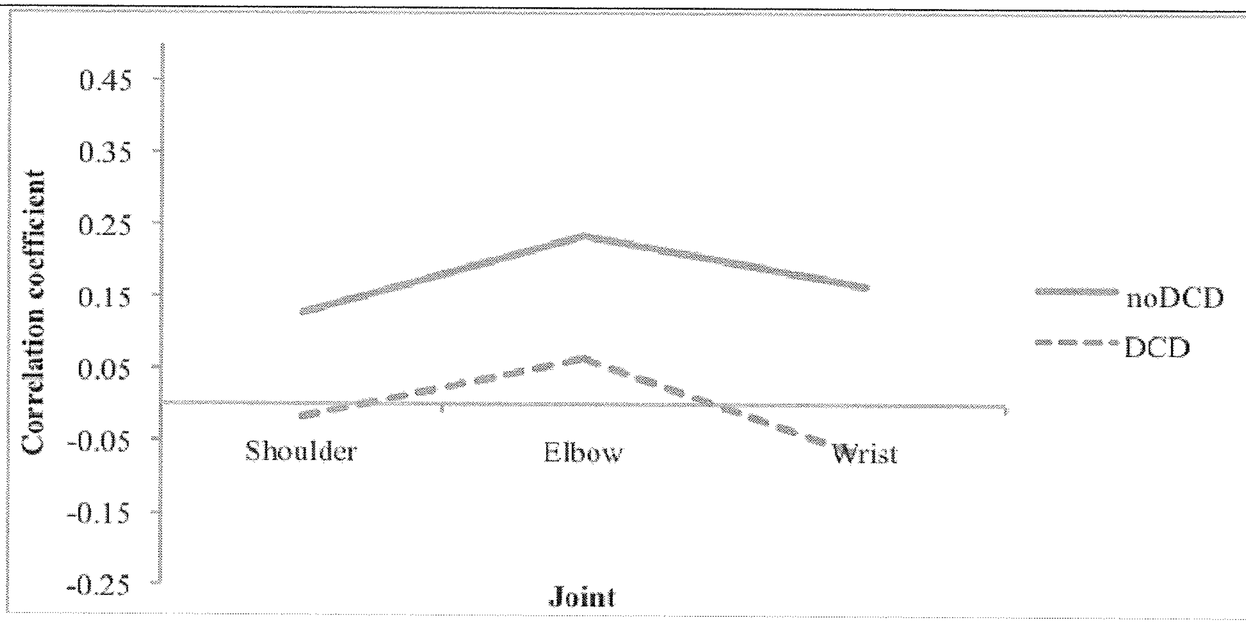

Figure 9. Relationship between net and passive torque at the shoulder, elbow, and wrist joints for the typically developing children (noDCD) and children with DCD (DCD).

Net and muscular torque. A significant interaction effect was found for the muscular torque utilization ($F(1,17) = 4.81$, $p < .05$, $\eta^2 = .05$) (*Figure 10*). The independent samples *t*-tests revealed that only significant between group differences were found at the wrist joint ($t(17) = 2.33$, $p < .05$, $d = .96$). The one-way ANOVA revealed that there were significant differences across the joints for the children with ($F(1,9) = 28.71$, $p < .001$, $\eta^2 = .76$) and without DCD ($F(1,8) = 30.14$, $p < .001$, $\eta^2 = .79$). For the DCD group, the subsequent dependent samples *t*-tests revealed that there were significant within group differences between the shoulder and elbow ($t(9) = 6.90$, $p < .001$, $d = 2.18$) and shoulder and wrist ($t(9) = 6.54$, $p < .001$, $d = 2.07$) with the shoulder joint having higher correlation coefficients in both comparisons. For the typically developing group, there were also significant differences between the shoulder and elbow ($t(8) = 8.39$, $p < .001$, $d = 2.80$), as well as the shoulder and wrist ($t(8) = 10.33$, $p < .001$, $d = 2.54$). In terms of stability of the net and muscular torque correlation coefficients, no significant differences were found.

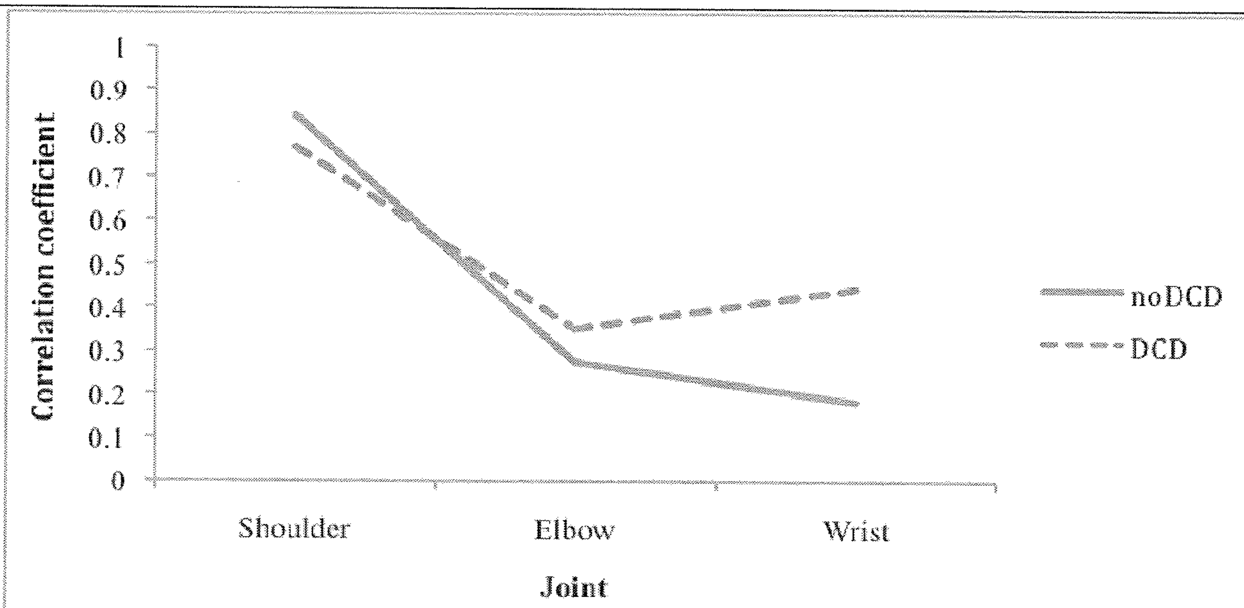

Figure 10. Relationship between net and muscular torque at the shoulder, elbow, and wrist joints for the typically developing children (noDCD) and children with DCD (DCD).

Discussion

It is known that children with DCD perform qualitatively different movement patterns compared to their age-matched peers. In most cases, these differences lead to lack of success when performing simple everyday activities. It is important to determine the root of these qualitative differences by examining the underlying coordination tendencies of this population, and whether they exhibit less than optimal movement patterns. There has been limited research that has examined whether or not children with DCD have issues with intra-limb coordination (e.g., Przysucha, 2011), but no research had examined if these coordination differences are constrained by less than optimal torque modulation tendencies. The following discussion will describe each group's movement functionality during the one-handed catch, followed by a description of coordination tendencies of the groups, and subsequently describe the underlying torque modulation tendencies exhibited by both the children with and without DCD.

Movement functionality

The first research question was answered by examining the level of success of the two groups when performing the one-handed catch. It was expected that the typically developing children would have more functional actions compared to the children with DCD (Van Waelvelde et al., 2004). The results confirmed this hypothesis. It was shown that the typically developing children performed the task with high success as they caught 85% of the balls during the task. This performance is considered optimal because in past research, Williams (1992) marked a success rate over 70% as proficient. Since the children were between 9 and 12 years of age, these data also confirm that one-handed catching matures between this age range, as consistent with past work completed by Savelsbergh and van Santvoord (1996). Upon the individual analysis of the typically developing children, it was found that there was homogeneity within this group. The child without DCD who was least successful at the task caught 70% of the balls, while the best performer caught 100% of the balls. This result means that all of the children were above the 70% level for task effectiveness.

The children with DCD, however, were not as successful at the task. As a group, children with DCD caught only 32% of the balls. In past literature this level of performance is indicative of movement problems (Williams, 1992). The individual analysis, however, confirmed that the children with DCD are heterogeneous as some boys caught as many as 60-70% of the balls while others caught as low as 10% of the balls. Thus, the results showed that some children with DCD still have issues with organizing actions at the intra-limb level, while the actions of other children with this disorder may be more effective.

Intra-limb coordination

To answer the second research question and determine if the lack of movement functionality was due to differences in coordination across the relevant joints, the degree and stability of spatial coupling (i.e., nature of coordination) was analyzed. This analysis allowed making inferences regarding how children with and without DCD solved the degrees of freedom problem, as put forward by Bernstein (1967).

Shoulder-elbow. It was hypothesized that the children without DCD would exhibit a high degree of spatial coupling between the shoulder and elbow joints (Przysucha, 2011). The data from this study did not confirm this notion. The typically developing children had a mean correlation coefficient of .69 at the shoulder-elbow joint pair. This result was also not consistent with past literature involving one-handed catching in adults. In research completed by Mazyn and colleagues (2006), the participants had a mean correlation coefficient of approximately .77 across all the ball speeds, ranging from 8.6m/s to 19.7m/s. These differences in past and present research may be due to the nature of the task. In Mazyn and colleagues' study, the ball was projected to an imaginary circle located 15cm above the participant's shoulder, while the ball was projected directly at the participant's shoulder in the task of this thesis. This difference in the task constraints could have affected the magnitude of the correlation coefficient because the shoulder was not required to be as actively involved to reach for the ball in the present task. This constraint ultimately could have reduced the range of motion of the shoulder joint and resulted in a lower correlation coefficient. Since there were differences in the degree of shoulder-elbow coordination in this thesis compared to Mazyn and colleagues' study, it is evident that invariant relationships between joints are arbitrary and dependent on the task constraints.

In terms of intra-subject variability, as expected from the hypothesis, the typically developing children had higher stability. This was consistent with past literature that used one-handed catching to evaluate intra-limb coordination (SD~.09) (Mazyn et al., 2006). This result means that the synergy exhibited by the typically developing children was consistently organized across trials.

It was expected that, compared to the typically developing children, children with DCD would exhibit weaker coupling between the shoulder and elbow joints. The data rejected this hypothesis as the children with DCD had significantly higher coupling between the shoulder and elbow joints (r = .80). This value, in relation to the typically developing peers, was even closer to the correlation coefficients presented in the work by Mazyn and colleagues (2006). In terms of intra-subject variability, the emerging spatial relations were less stable compared to the children without DCD (M_{dcd} = .12 vs. $M_{w/odcd}$ = .09). Although there were significant differences between groups in relation to intra-subject variability, both values were low. This result indicates that the children with DCD also formed a consistent synergy between the shoulder-elbow joints to perform the one-handed catch. Since typically developing children are considered the *gold standard* for intra-limb coordination, it is unclear whether the synergy exhibited by the children with DCD was suitable for the task.

In addition to the magnitude and stability of the correlation coefficients, angle-angle plots further described how the statistical differences coincided with qualitative differences at the behavioural level. Due to a low standard deviation for both groups at the shoulder-elbow ($M_{noDCD} = .12$, $M_{DCD} = .09$), one child was used to represent the performance of the majority of children in his respective group. Refer to Appendix J for the individual results to confirm this logic.

Even though the inferential statistics revealed that there were between group differences in spatial coupling at the shoulder-elbow, the process measures failed to support such findings. As evident from the angle-angle plots (*Figure 11*), children with (right) and without (left) DCD performed the movements in a qualitatively similar manner. Both groups exhibited a segmented movement pattern by flexing the elbow, followed by flexion of the shoulder to catch the ball. This ultimately means that, despite the presence of bi-articular muscles, the shoulder and elbow relations are constrained by the task and consequently were decoupled.

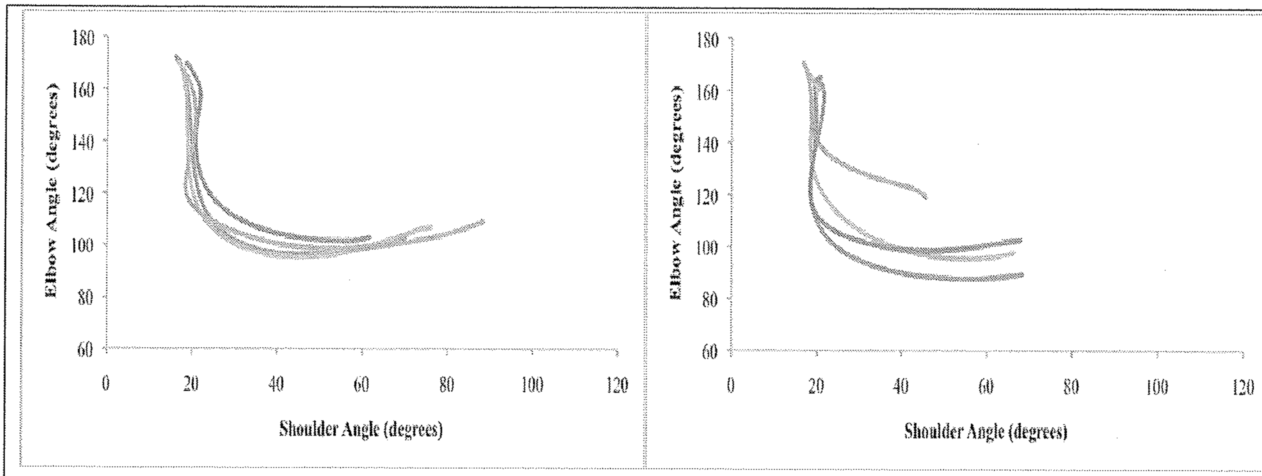

Figure 11. The angle-angle plots for the shoulder and elbow of each group across five trials. The graph on the left represents the typically developing child, while the graph on the right represents the child with DCD.

Aside from the degree of coordination, another important feature of the shoulder-elbow synergy is stability. As evident from the angle-angle plots, the typically developing child performed the five catching trials with similar spatial relations, while the child with DCD performed a different movement pattern on each attempt. This result indicates that there was correspondence between the inferential statistics and the process measure in relation to stability. Overall, the variability in shoulder-elbow relations exhibited by the children with DCD gives insight to the fact that children with this disorder do not organize a consistent movement pattern from trial to trial when catching a ball (e.g., Utley & Astill, 2007).

The above group and individual analysis on the degree and stability of the shoulder and elbow relations provided information regarding intrinsic dynamics of children with and without DCD. Evidence from the angle-angle plots revealed that the children with DCD performed less stable and weaker coupling between the joints across every trial. The typically developing children also decoupled the joints across the trials. This coupling ultimately means that children with and without DCD had the same coordinative tendency and solved the degrees of freedom problem in a similar manner at the shoulder and the elbow. It could be that the coordination tendencies were the same due to the task constraints (Newell, 1985). Upon individual analysis, it was evident that nine out of the ten children with DCD contacted the ball across all the trials. It could be that the shoulder-elbow synergy was necessary for transporting the arm. It was apparent, however, that the coordinative tendency exhibited by both groups resulted in different levels of movement functionality (i.e., number of balls caught). This inference indicates that the nature of shoulder-elbow coupling may be an essential variable for the transport phase of the action, but not for the fine tuning of the one-handed catch.

Elbow-wrist. Since the shoulder-elbow relations could potentially be non-essential to catching the ball, and coupling is joint specific, the spatial relations between the elbow and wrist joints were examined. It was expected that the children without DCD would exhibit tighter coupling at the elbow-wrist joints compared to the children with DCD (Przysucha, 2011). This hypothesis was confirmed by the data. Children without DCD had a higher mean correlation coefficient (r = .80) compared to the children with DCD (r = .62). In addition, the typically developing children, in fact, presented with higher magnitude of correlation coefficients at the elbow-wrist compared to their shoulder-elbow relations. This result exemplifies that the degree of spatial coupling is joint specific (Lacquaniti & Soechting, 1982; Soechting & Lacquaniti, 1981).

When analyzing intra-subject variability, it was evident that along with tight coupling, the elbow-wrist relations were also consistent across trials in the typically developing children. The coordination tendencies for both joint pairs were stable for this group. This result indicates that, if the shoulder-elbow joint is considered a synergy because of low intra-subject variability, that the elbow-wrist is also an effective unit of action in this task.

The tight elbow-wrist coupling evident in the present research was consistent with past literature involving one-handed catching. In Mazyn and colleagues' work (2006), a group of adult participants attempted to catch a ball one-handed at varying speeds and the resulting correlation coefficient of the elbow-wrist was relatively high (r ~.80) and comparable to those observed in the present research. This comparison further confirms the notion that typically developing children develop adult-like intra-limb coordination between the ages of 9 and 12. In past literature involving uni-manual reaching (Lacquaniti & Soechting, 1982), the elbow and wrist correlation coefficients were much lower. In Lacquaniti and Soechting's study, the wrist was weakly coupled and it was controlled independently during the reaching task. Even though weaker coupling of the elbow-wrist has been more prevalent in past research (Lacquaniti & Soechting, 1982), the task of the present thesis could have constrained the typically developing children to couple the elbow and wrist joints. The ball was projected to the participant with a substantial arc and this trajectory could have constrained the wrist to be more actively involved to adapt to the incoming ball. Also in Mazyn and colleagues' study (2006), as the task demands increased, or the ball sped up, the degree of coupling between the elbow and wrist also increased. This joint pair coupling is considered essential because the relationship grew stronger and became more stable across trials as the task became more difficult. As a result, it is evident that the elbow and wrist formed a synergy that was essential to catching the ball with one-hand.

The typically developing children presented tight and stable coupling of the elbow-wrist joint during the task, but this result was not exhibited by the children with DCD. As expected from the hypothesis, children with DCD exhibited weaker coupling between the elbow and wrist joints. Since intra-limb coordination exhibited by typically developing children is the gold standard, this weak coupling indicates that children with DCD have not formed a mature synergy between the elbow and wrist joints. In addition, the spatial relations of this joint pair were also significantly less stable across trials for the children with DCD as compared to their typically developing peers (M_{dcd} = .21 vs. $M_{w/odcd}$ = .09). This lack of stability could have affected the children with DCD's success, as it would be complicated to control the action if the movement pattern was different from trial to trial. This result further indicates that children with DCD have not formed a mature synergy between this joint pair.

To determine how the elbow-wrist relations appeared behaviourally, angle-angle plots were analyzed. Once again, both groups exhibited low standard deviation between participants (M_{noDCD} = .15, M_{DCD} = .19). As a result, one child was used to represent the majority of children in his respective group. Refer to Appendix J for the individual results.

As seen in the profile of a typically developing child (*Figure 12*, left) the angle-angle profiles revealed that the elbow and wrist joints were tightly coupled. It is evident that the child starts the catching action by co-occurring flexion of the elbow and wrist joint. This relationship continued throughout the action right up until ball contact. At contact, there was a reversal in elbow angular displacement to adjust the hand to the incoming ball flight. This pattern was also very stable across trials.

The typically developing child had a strong, consistent spatial relationship between the elbow and wrist joints. The child with DCD, however, presented with weaker and less stable coupling across trials (*Figure 12*, right). As evident from the plots, there was a weak relationship between this joint pair because the children with DCD produced large and random changes of wrist movement in relation to elbow movement. It is evident that this group of children excessively *freed* the wrist joint. Upon individual analysis (Appendix J), it was evident that, in the majority of the participants, weaker coupling of the elbow-wrist coincided with less effective actions.

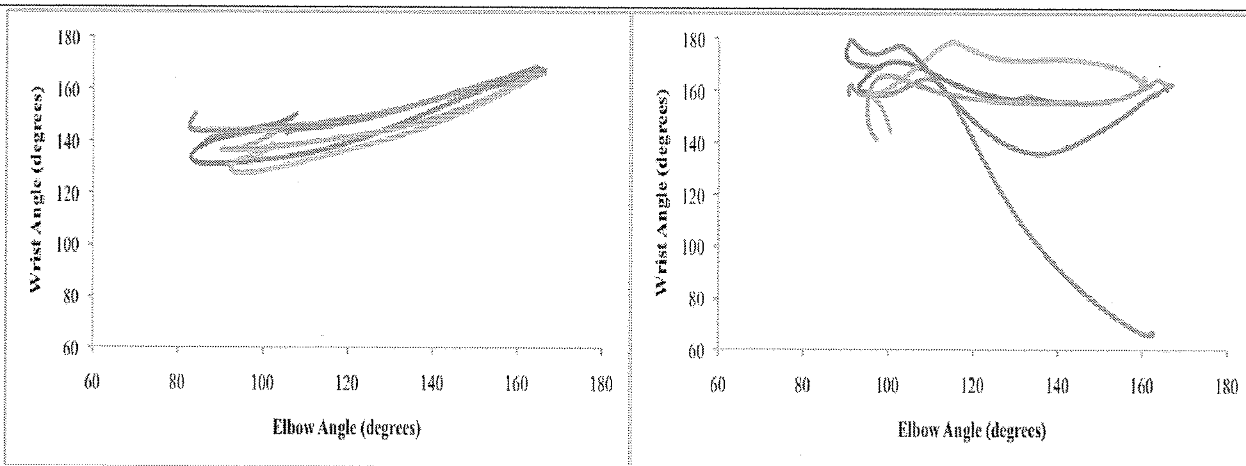

Figure 12. The angle-angle plots of the elbow-wrist joint for both groups across five trials. The graph on the left represents the typically developing child, while the graph on the right represents the child with DCD.

It is speculated that a combination of individual soft constraints (i.e., preferred coordination tendencies) and the nature of the task ultimately influenced the spatial relations exhibited by both groups. In past research (Lacquaniti & Soechting, 1982), the elbow-wrist was not as strongly coupled, however, in the present study the task constraints could have led to differences in the degree of coupling. The child without DCD accomplished the task by coupling the elbow and wrist joint. The child with DCD, however, *freed* the wrist joint. This soft constraint led to weaker coupling, which coincided with less functional actions. This freeing tendency was also present in the majority of children with DCD. It is speculated that the elbow-wrist synergy was necessary to stabilize the location of the palm/fingertips of the hand in relation to the ball flight (i.e., perpendicular to ball flight) to increase task effectiveness. The above group and individual analysis revealed that children with and without DCD solved the degrees of freedom problem at the distal joints. Since there were between group differences in elbow-wrist, but not shoulder-elbow relations, these results show that the lack of movement functionality, exhibited by children with DCD, may be jeopardized by the nature of elbow-wrist coupling.

Summary of intra-limb coordination. The data revealed that children with and without DCD organize intra-limb actions differently at the distal segments. Both groups de-coupled the shoulder-elbow joints, while only the typically developing children coupled the elbow-wrist joints. This between group difference in elbow-wrist relations indicates that intra-limb coordination could develop in a proximal to distal direction (Jensen et al., 1995). In addition, the children with DCD had a universal tendency to decouple the relevant joints. Opposing Bernstein's original hypothesis (1967) in relation to joint *freeing* and *freezing*, the nature of coupling was joint and group/population specific, as the typically developing children decoupled the shoulder-elbow, but coupled the elbow-wrist joints. These coordination tendencies were more in line with Newell's model of constraints (1985). In terms of stability, the children with DCD performed less stable movement patterns at the elbow-wrist joint pair. This result further exemplifies that children with DCD have not formed mature synergies at the distal joints. Intra-limb coordination tendencies exhibited by the typically developing children were assumed to be the most functional/optimal way to complete the task because they coincided with high success on the task. The coordination tendencies of the children with DCD, on the other hand, were less than optimal because their actions were not effective. These overall results indicate that, due to different intrinsic dynamics, the children with and without DCD solved the degrees of freedom problem differently at the essential variable (i.e., coupling the distal joints) for the task.

Torque modulation

It was evident from the correlation coefficients and angle-angle plots that children with and without DCD exhibit different coordination tendencies at the distal joints. It could be that these qualitative differences are due to biomechanical constraints on coordination, namely torque modulation. To examine the third research question (i.e., torque modulation), the relationship between net and passive (NET-PAS) torque and net and muscular (NET-MUS) torque was used to examine torque modulation differences. In addition, angle-angle plots were analyzed alongside individual torque profiles to determine if differences in coordination coincided with differences in torque modulation tendencies.

Net and passive torque. The first analysis examined the relationship between NET and PAS torque across the shoulder, elbow, and wrist. It was hypothesized that children with DCD would utilize similar amounts of passive torque at the shoulder or leading joint and less passive torque at the distal or subordinate joints (i.e., the elbow and wrist in this task) compared to the typically developing children (Bastian et al., 2000; Dounskaia, 2010). The data partially confirmed the hypothesis as the typically developing children utilized more passive torque across all the joints.

In accordance with the leading joint hypothesis (Dounskaia, 2005), the distal joints, in this context the elbow and wrist, would use the passive torque from the leading joint (i.e., shoulder), while the leading joint would be organized as a single-joint action. As evident from the data, the typically developing children were able to use the passive torques to contribute to joint movement at all the joints, more importantly the elbow and wrist joints. A similar finding was exhibited in past research (Dounskaia et al., 2002; Dounskaia et al., 1998). The elbow and the wrist were able to use the interactive torque (a part of passive torque) from the leading joint to produce joint movement. Since the children without DCD were able to utilize passive torques at the distal joints, therefore making these joints subordinate, it could be that torque modulation is mature between 9 and 12 years of age.

As expected, children with DCD utilized passive torque to a lesser extent as evident from the lower correlation coefficients. Since passive torque was not used to contribute to, or counteract, joint movement, it is speculated that this torque was unaccounted for by the CNS during movement execution and could have contributed to excessive joint movements. In Bastian and colleagues' (2000) study, people with cerebellar lesions had similar torque modulation to the atypically functioning participants in the present thesis. It was found that people with cerebellar lesions, in past literature (Bastian et al., 2000), were unable to account for interactive torques at a stationary joint (i.e., the shoulder) and created excessive joint movement leading to endpoint errors. It could be that the same torque modulation issues presented by individuals with deficits, during the pointing task, underlie the problems children with DCD have while catching a ball in the current study. Since the location of wrist was essential to catching the ball in the present research, it is speculated that the lack of passive torque utilization at the elbow and wrist joints could have manifested themselves as end-point errors (i.e., incorrect ball contact on the hand). Ultimately, incorrect hand location in relation to the ball's trajectory would cause less effective actions during the catching task.

Net and muscular torque. To further examine torque modulation tendencies of the two groups, the relationship between NET-MUS torque was compared across the shoulder, elbow, and wrist. The first hypothesis was that, for both groups, the shoulder joint would use more muscular torque to produce joint movement compared to the distal joints—as consistent with the leading joint hypothesis (Dounskaia, 2005). The data confirmed this hypothesis. The inferential statistics revealed that the shoulder joint utilized significantly more muscular torque compared to both the elbow and wrist joint in both groups. Ultimately, this notion confirms that both groups used the shoulder as the leading joint for the task because the shoulder joint kinetics were similar to a single-joint movement, marked by the high NET-MUS correlation coefficient, while the distal joints were less reliant on muscular torque (Dounskaia, 2005).

The next and more important hypothesis was related to whether or not the groups utilized muscular torque differently. It was also hypothesized that children with DCD, compared to children without DCD, would utilize less muscular torque at the shoulder or leading joint and more muscular torque at the distal or subordinate joints (Bastian et al., 2000; Dounskaia, 2010). The data only partially confirmed this hypothesis, as the analysis revealed that there were only significant between group differences at the wrist joint. The data indicated that the typically developing children utilized less muscular torque at the wrist joint to catch the ball. This result was consistent with research conducted by Dounskaia and colleagues (1998), as minimal muscular torque was needed to move the wrist joint during the cyclical uni-directional elbow-wrist action. Koshland and colleagues (2000) studied the wrist joint exclusively during a three-joint movement and found that the magnitude of muscular torque did not coincide with wrist net torque. Since typically developing children used minimal muscular torque to move the wrist joint, as consistent with elements of the adults' performance in past research (Dounskaia et al., 1998; Koshland et al., 2000), it confirms that torque modulation becomes adult-like for the typically developing children between the ages of 9 and 12.

From the inferential statistics, children with DCD, as hypothesized, evidently utilized more muscular torque at the wrist joint. This result means that this group may not have fully accounted for the passive torques produced at the wrist and, compared to the typically developing children, exhibited less than optimal torque modulation at the distal joint. As a result of this torque modulation tendency, it was suggested that the children with DCD attempted to control the wrist joint independently of the elbow and shoulder motion. A similar pattern of passive torque utilization was also evident in research carried out by Dounskaia and colleagues (1998) because when the movement pattern deteriorated, passive torque could not be accounted for. Also, this poor muscular torque utilization, exhibited by the children with DCD, could have contributed to excessive wrist excursions and jeopardized the catching ability of this group.

It is evident that, compared to the typically developing children, children with DCD utilized less passive torque at all the relevant joints, while using excessive muscular torque at the wrist joint. There were no between group differences in intra-subject variability. This result means that, compared to the typically developing children, the children with DCD exhibited similar stability of their torque modulation tendencies. This notion indicates that both groups exhibited a consistent torque modulation tendency across the trials. Thus, it was determined that differences in movement functionality are attributed to the degree passive/active torque is modulated at the relevant joints, rather than lack of a stable torque profile. From these inferences, it is evident that biomechanical factors, namely torque modulation tendencies and joints involved, affected movement organization in children with DCD. This type of constraint could have forced the children with DCD to exhibit different coordination tendencies. Since this is only a speculation, individual scatter plots of NET-PAS and NET-MUS torque were paired alongside angle-angle plots to determine if coordination patterns coincided with certain torque modulation tendencies.

Kinematics and kinetics. As previously mentioned, there was a relatively low between group standard deviation at the shoulder-elbow (M_{noDCD} = .12, M_{DCD} = .09) and elbow-wrist (M_{noDCD} = .15, M_{DCD} = .19) joint pairs for both groups. For this reason, only one child was used to represent his respective group. A child with the most representative spatial relations, and similar torque modulation tendencies, for his respective group (Appendix J) was used to analyze the kinematics with the kinetics.

Shoulder-elbow vs. NET-MUS and NET-PAS relations. From the kinematic analysis, it was evident that children with and without DCD de-coupled the shoulder and elbow joints. Since the angle-angle plots revealed that the qualitative differences between groups were marginal, it was expected that there would be no inter-group differences at the kinetic level. The data partially confirmed this hypothesis. As evident from the angle-angle plots (*Figure 13*) both children exhibited a segmented movement pattern between the shoulder and elbow joints.

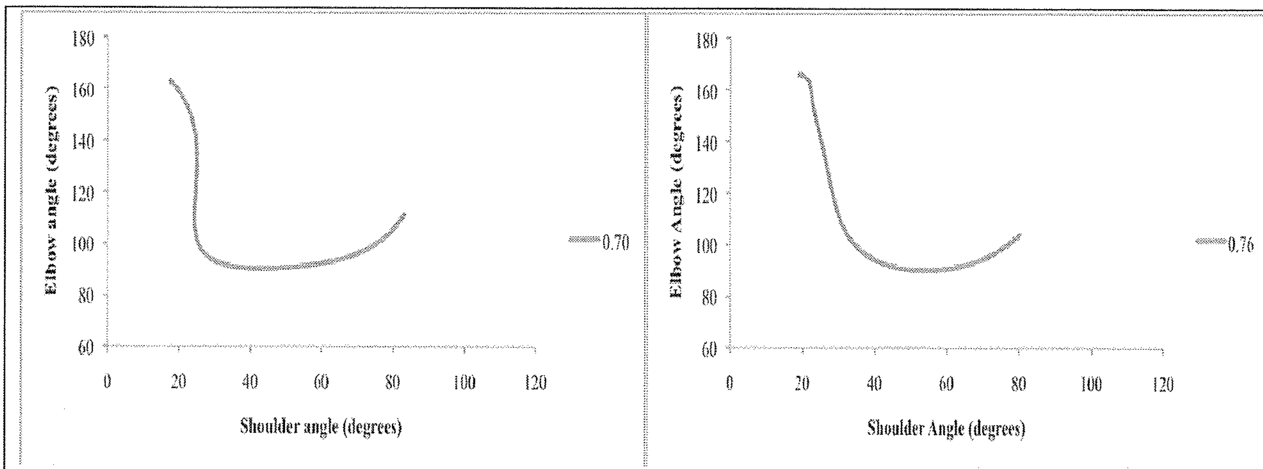

Figure 13. Angle-angle plots for the shoulder and elbow joint. The graph on the left represents the child without DCD, while the graph on the right represent the performance of a child with DCD.

This decoupling also coincided with similar muscular torque utilization, as evident from *Figure 14* (top left and right). Both groups used primarily muscular torque to produce movement at the shoulder joint. This result is consistent with the leading joint hypothesis (Dounskaia, 2005) because the shoulder joint is expected to produce its movement by using primarily muscular torque. In addition, both children utilized a moderate amount of muscular torque at the elbow joint indicated by the correlation coefficient (*Figure 14*, bottom left and right). This torque modulation tendency suggests that each child attempted to control the elbow joint independent of the shoulder joint, as confirmed by the spatial relations. In addition, there was a one to one correspondence between kinematics and kinetics. It is speculated that this muscular torque utilization was suitable for the transport phase of the catch for both groups.

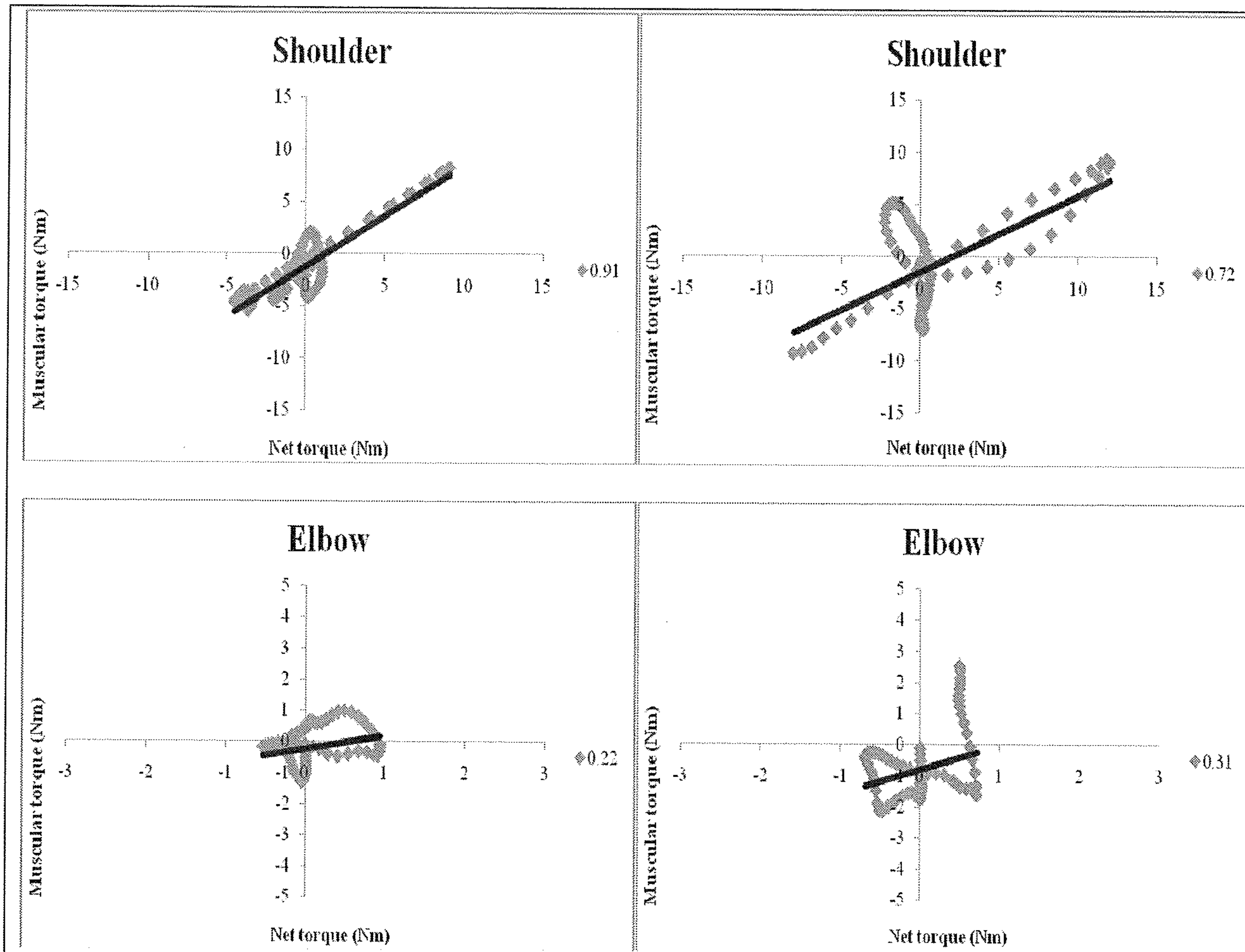

Figure 14. Relationship between net and muscular torque at the shoulder and elbow joint for a child with (right) and without (left) DCD.

In contrast to the net and muscular torque relations and the hypothesis, there were differences in passive torque utilization at the shoulder and elbow joint. As *Figure 15* shows, the child without DCD (top left) utilized less passive torque at the shoulder joint in comparison to the child with DCD (top right). Although this is indicative of different underlying dynamics at the shoulder joint, the leading joint hypothesis suggests that the shoulder's movements are not controlled by passive torques, and rather are organized as a single-joint movement (Dounskaia, 2005). This notion indicates that differences in passive torque utilization at the shoulder should not correspond to differences at the kinematic level between the two children.

Similar to the shoulder joint, dynamics of the elbow joint were different between the participants. The scatter plots (*Figure 15*) showed that the child without DCD (bottom left) utilized more passive torque at the elbow joint in comparison to the child with DCD (bottom right). According to the leading joint hypothesis (Dounskaia, 2005), the elbow joint should be subordinate during this uni-manual action. The net and passive torque relations evident here at the elbow joint indicated that this joint was in fact subordinate in the example of a child without DCD. This was not true, however, for the child with DCD. This result is consistent with developmental research (Konczak et al., 1995; Zernicke & Schneider, 1993). It was shown that infants were not able to regulate passive torques effectively at the elbow joint, which translated into decoupling at the kinematic level. In addition, research examining the performance of people with cerebellar lesions during a pointing task, showed that they could not regulate passive torque at the subordinate joint and ultimately caused spatial errors in the end point (Bastian et al., 2000). In the context of the present study, it is speculated that lack of passive torque modulation could have also manifested as spatial errors at the end-point (i.e., location of the hand). These comparisons gave evidence that the child with DCD has not developed a torque modulation tendency that accounts for passive torques and this tendency could have caused less functional actions.

Although the shoulder-elbow relations were similar for both groups, the passive torque utilization was different at the elbow, indicating that there may not be correspondence between kinematics and kinetics. A similar postulation was made by Dounskaia and colleagues (2002), as they hypothesized that ineffective passive torque modulation may affect coordination patterns of the elbow-wrist joints more than shoulder-elbow pairing. It is suggested that the degree of passive torque utilization at the elbow, exhibited by the child without DCD, was needed for the elbow-wrist relationship instead. For instance, if passive torque was not utilized at the elbow, it could have led to an error in elbow action and affected the elbow-wrist relationship. In the context of the present task, this change in elbow-wrist pattern, which is speculated to be the essential variable, could have lead to catching errors.

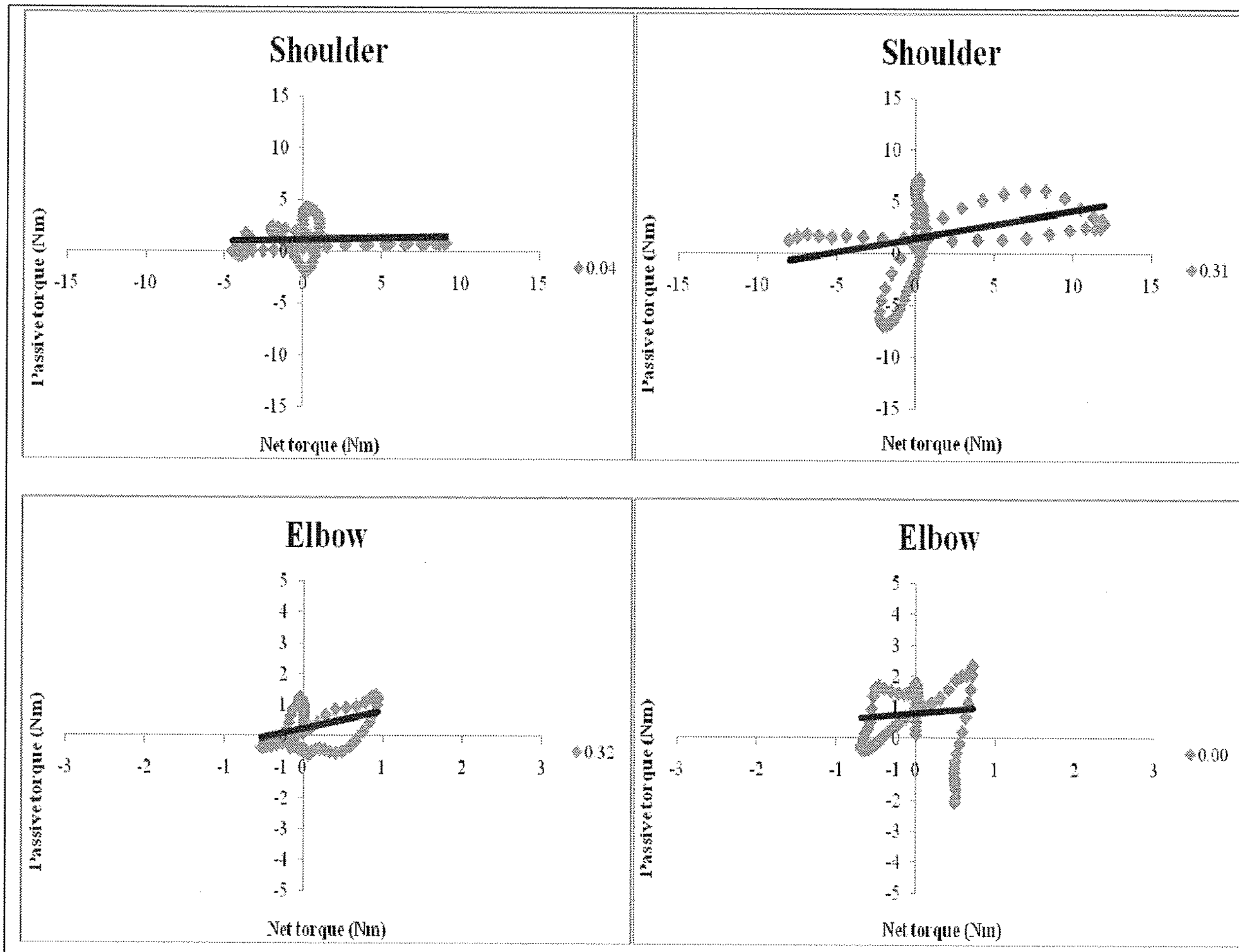

Figure 15. Relationship between net and passive torque at the shoulder and elbow joints for a child with (right) and without (left) DCD.

Elbow-wrist coordination vs. NET-MUS and NET-PAS relations. Since the elbow-wrist joint pair was considered the essential variable for the catching task, these joints were also analyzed. The net and muscular torque relations were compared first followed by the net and passive torque relationship at the elbow and wrist. The data from this research, and the pilot, showed that tight coupling of the elbow and wrist joints, in the positive direction, coincided with utilizing both passive and active torque to contribute to the net torque at the distal joint (i.e., the wrist). Decoupling, however, coincided with utilizing more muscular torque in relation to passive torque at the distal joint. As previously stated, children with DCD had weaker coupling of the elbow-wrist joint compared to the typically developing children. Hence, it was expected that these differences in coordination tendencies would coincide with different torque modulation at the elbow and wrist joints. The data confirmed this hypothesis. As evident from *Figure 16*, the typically developing child (left) tightly coupled the elbow and wrist joints for the majority of the movement, followed by making a correction at the wrist joint to catch the ball. By examining the elbow-wrist relations of a child with DCD (*Figure 16,* right), it is evident that this child decoupled the elbow-wrist pair and performed the one-handed catch in a qualitatively different manner compared to his peer without DCD. The child with DCD had excessive flexion and extension actions of the wrist joint, indicating that both the elbow and wrist joint were organized independently.

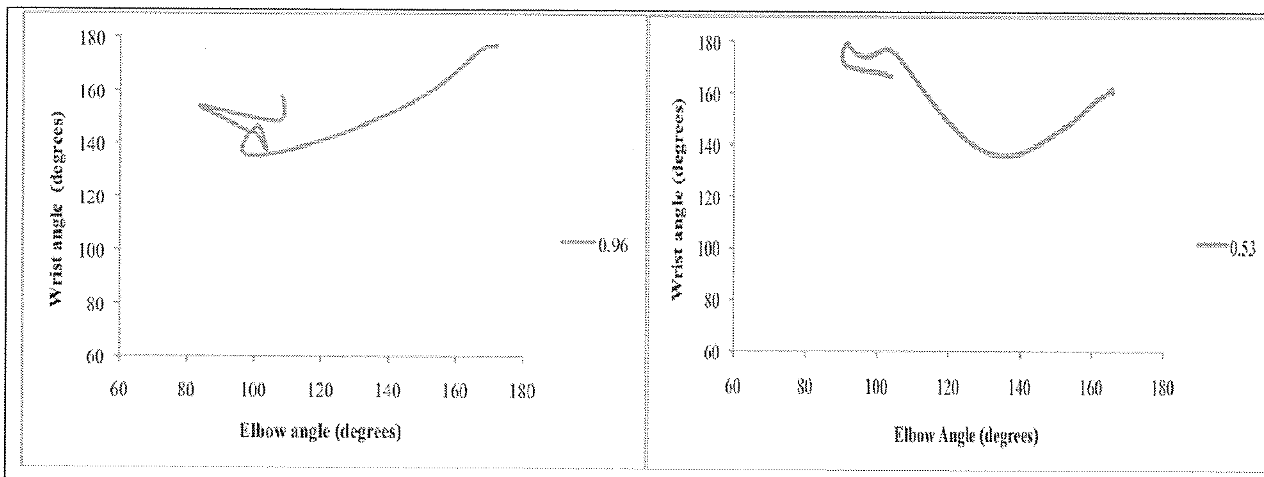

Figure 16. Angle-angle plots for the elbow and wrist. The graph on the left represents the child without DCD, while the graph on the right represents the performance of a child with DCD.

This tight coupling, exhibited by the typically developing child, was constrained by his torque modulation tendency. The child without DCD (*Figure 17*) utilized more muscular torque to contribute to net torque at the elbow (top left) compared to wrist (bottom left). This torque modulation tendency allowed the wrist joint to be subordinate. The behaviour of a typically developing child was consistent with elements of the adults' torque modulation tendencies as reported by Dounskaia and collegues (1998). During the uni-directional cyclical action (that is similar to the catching action), the overall net torque at the wrist did not coincide with the magnitude of muscular torque. Due to similarities in muscular torque utilization in the present and past research (Dounskaia et al., 1998), it is suggested that the typically developing child in the present study, and hence the entire group, have mature muscular torque modulation tendencies at the distal joints.

The correponding torque profile, of the child with DCD, coincided with decoupling the elbow and wrist joints. This child with DCD (*Figure 17*) utilized a moderate amount of muscular torque at the elbow joint (top right), however, muscular torque modulation at the wrist joint was drastically different. The child with DCD utilized primarily muscular torque to contribute to net torque at the wrist joint (bottom right). This torque modulation tendency could have caused the random changes in the wrist's flexion/extension. In Dounskaia and collegues (1998) research, as the task became more complicated, the muscular torque was not able to regulate the passive torque effectively. To confirm this notion, the net and passive torque relations were also examined at the elbow-wrist.

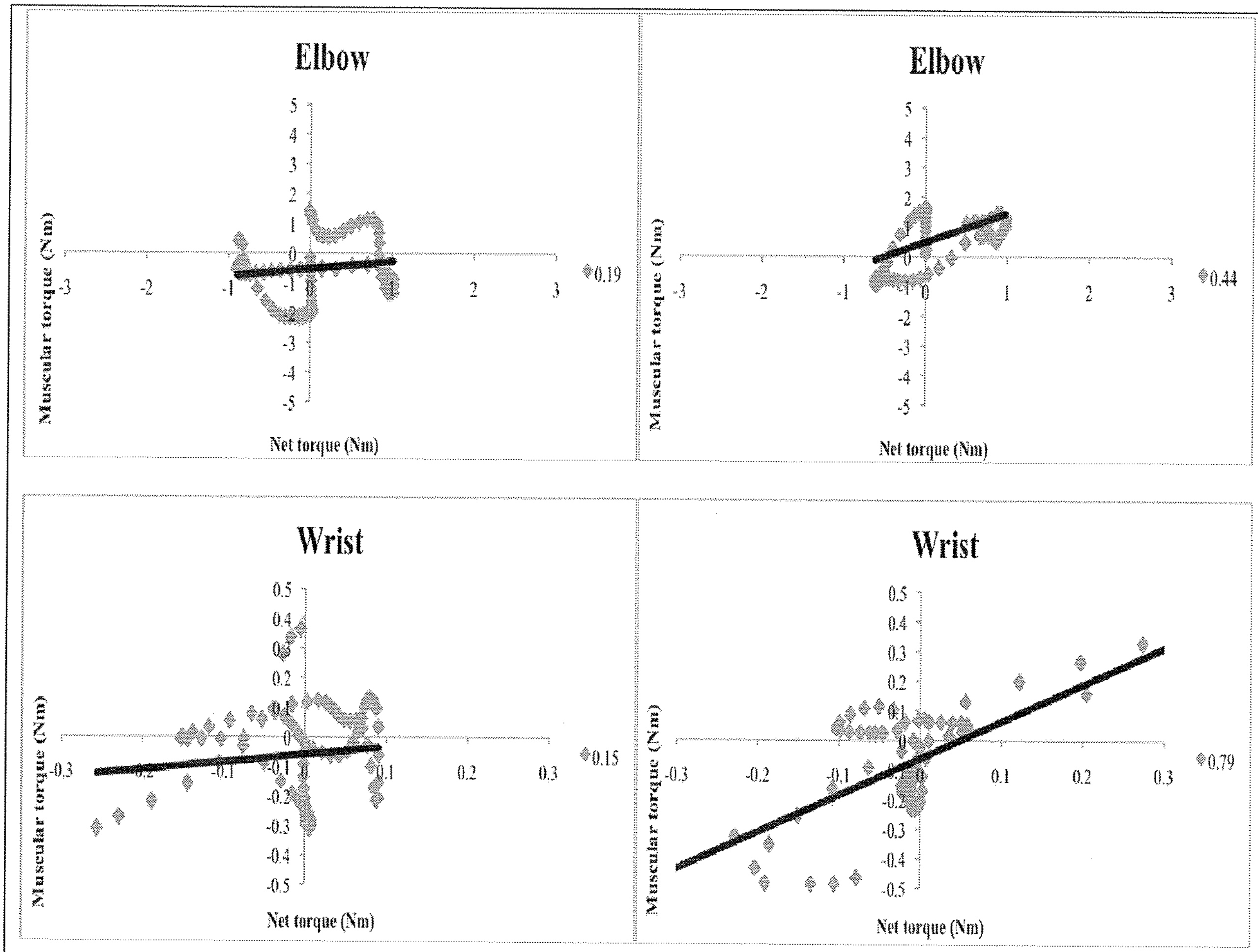

Figure 17. Relationship between net and muscular torque at the elbow and wrist joint for a child with (right) and without (left) DCD.

The torque profile of a typically developing child (*Figure 18*) revealed that there was a positive correlation between net and passive torque at the elbow joint (*Figure 18*, top left). This result indicates that the elbow utilized passive torque (from the shoulder) and it was postulated that this utilization was necessary to ensure that the elbow-wrist relationship remained intact (i.e., there were no errors in the elbow joint's movement due to unaccounted for passive torque). The wrist profile (*Figure 18,* bottom left) revealed that the typically developing child used a moderate amount of passive torque, from the shoulder and elbow, to contribute to the net torque at the wrist. This result is consistent with elements of past research (Dounskaia et al., 1998), as the wrist utilized passive torque from the other joints involved to contribute to the overall net torque. As a result, it is evident at the behavioural level that the typically developing children coupled the elbow and wrist joints and this coordinative tendency coincided with adult-like passive torque utilization at the distal joints.

On the other hand, the child with DCD presented with different passive torque modulation at the elbow and wrist joints. As evident in *Figure 18*, there was a weak relationship between net and passive torque at the elbow (top right), meaning that passive torque was not utilized to contribute to the net torque at the elbow. It was suggested that utilizing less passive torque at the subordinate joint could have manifested as errors in the spatial location of the hand, as consistent with past research (Bastian et al., 2000). Large differences in passive torque modulation emerged at the wrist joint. The wrist profile (*Figure 18*, bottom right) indicated that the passive torque was used to oppose the net torque at the wrist, instead of utilizing the passive torque as evident in the typically developing child. This result was similar to people with cerebellar lesions in past research (Bastian et al., 2000). The movement patterns of the atypically functioning individuals deteriorated because of incorrectly utilzing passive torque at the subordinate joint as the task demands increased. Similar to the shoulder-elbow torque modulation for the child with DCD, the subordinate joint (i.e., the wrist) did not utilize passive torque effectively. Behaviourally, lack of passive torque modulation coincided with decoupling the elbow and wrist joints. Since the child performed the task less effectively, it is speculated that the difference in passive torque modulation at the wrist joint could have been a limiter on intra-limb coordination.

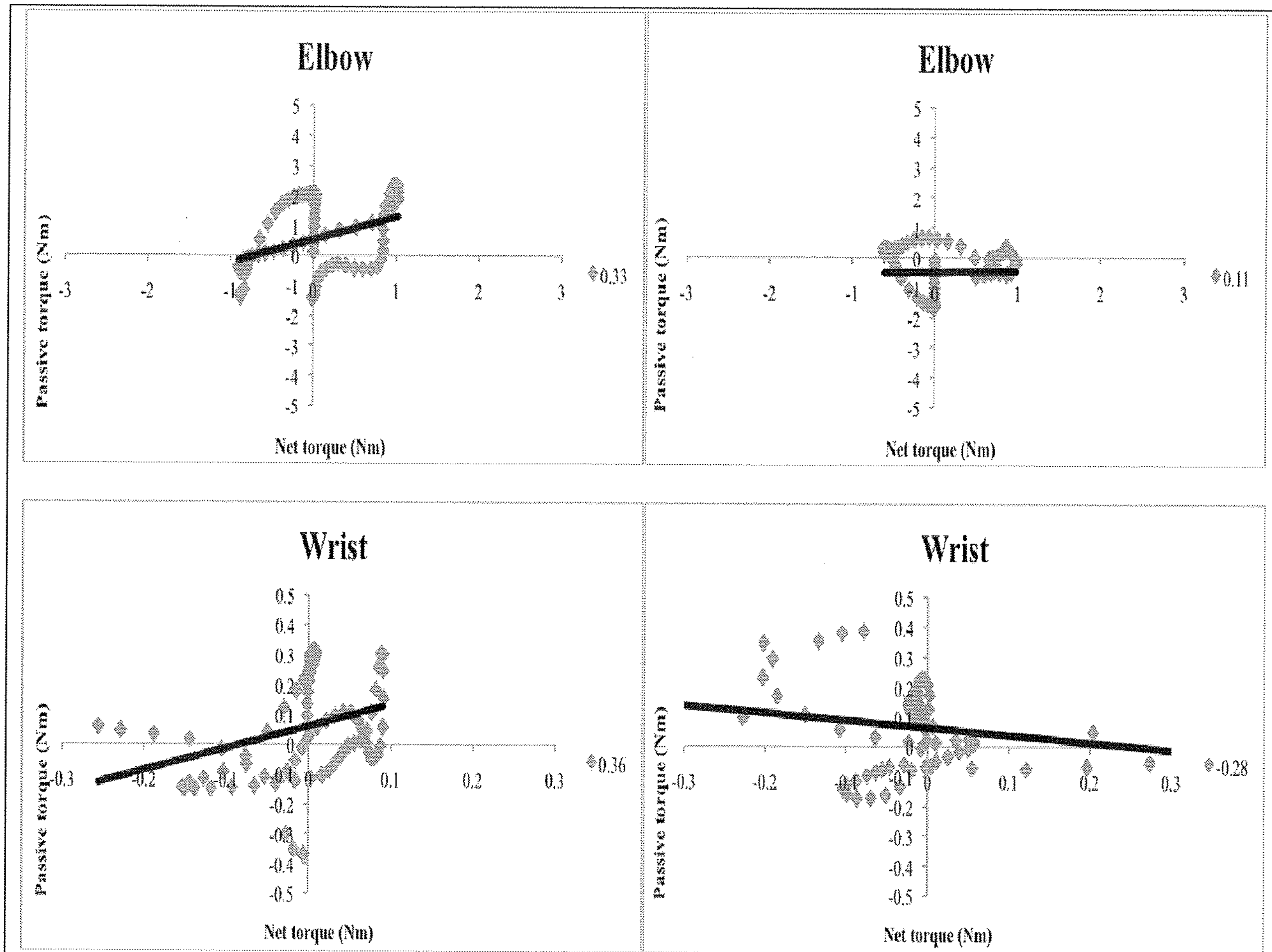

Figure 18. Relationship between net and passive torque at the elbow and wrist joints for a child with (right) and without (left) DCD.

Summary of torque modulation. The data showed that there were differences in torque modulation tendencies between typically developing children and children with DCD. At the shoulder-elbow joint, both groups utilized muscular torque in a similar manner. The shoulder joint used primarily muscular torque, while less muscular torque was used at the elbow joint. In terms of passive torque modulation, the children with DCD used less passive torque at the elbow. Despite the differences in underlying dynamics at the elbow, torque modulation of both groups resulted in de-coupling of the shoulder and elbow joint. It was suggested that utilizing passive torque at the elbow was more important for the essential variable (i.e., the elbow-wrist relationship) and did not affect the shoulder-elbow spatial relations. When investigating the elbow and wrist joints, it became apparent where torque modulation deteriorated in the children with DCD. The children with DCD utilized less passive torque at the elbow. Since they did not account for this passive torque, there could have been errors in the action of the elbow, which could have manifested as an end-point error (i.e., location of the hand). At the wrist joint the child with DCD used primarily muscular torque to control this joint, while the typically developing child used more passive torque. This torque modulation tendency, exhibited by the child with DCD, could have caused random changes in wrist action, as evident from the spatial relations, and ultimately led to failure of the task.

The typically developing children has underlying dynamics that were consistent with the leading joint hypothesis (Dounskaia, 2005), as the leading joint (i.e., the shoulder) used primarily muscular torque, while the subordinate joints (i.e., elbow, wrist) used passive torque to produce their action. Since utilizing passive torque at the subordinate joints is essential for organizing different coordination patterns (Dounskaia, 2010), the torque modulation tendencies of children with DCD were less than optimal and less effective. This result was consistent with patterns (tendencies) evident in the pointing actions of atypically functioning individuals (Bastian et al., 2000). Since children with DCD performed actions similarly to persons with cerebellar lesions, it is speculated that they may have a dysfunction in their cerebellum (Cantin et al., 2007). In terms of the task, present data suggests that less than optimal ability to control active and passive torque at the distal joints jeopardizes the performance of the catching action. Since the coordination tendencies at the elbow-wrist were an essential variable for the task in this thesis, the lack of movement functionality could potentially be constrained by how passive and active torque is modulated at the elbow and wrist joints.

Chapter 5: General Discussion

The existing research provides evidence that children with DCD perform catching tasks poorly in comparison to typically developing children (Astill 2007; Deconinck et al., 2006; Estil et al., 2002; Przysucha, 2011; Przysucha & Maraj, 2010; Utley & Astill, 2007; Utley et al., 2007; Van Waelvelde et al., 2004). In terms of one-handed catching, past research (Estil et al., 2002) indicated that children with DCD exhibit more spatial errors at the end-point when intercepting a ball. Although it was not explicitly studied in Estil and colleagues study, it was postulated that these spatial errors could have led to less functional actions. The present study added to past research (Deconinck et al., 2006; Estil et al., 2002) and suggests that, during a multiple degrees of freedom catch, the errors in catching exhibited by the children with DCD could be attributed to differences in spatial relationships between the distal joints.

In terms of coordinative tendencies, the children with DCD exhibited a universal tendency to decouple the relevant joints (Przysucha, 2011), while the nature of decoupling/coupling was joint specific for the typically developing children. The present research showed that the lack of success exhibited by the children with DCD was due to differences in coordinative tendencies at the distal joints. In the present research, the task influenced the way the two groups organized the goal-directed action and is consistent with Newell's (1985) original idea that constraints force certain movement patterns to emerge. The nature of the task could have constrained the relationships between the shoulder-elbow and elbow-wrist to be different compared to other studies involving uni-manual actions (Soechting & Lacquaniti, 1981; Lacquaniti & Soechting, 1982). The elbow-wrist coupling of the typically developing children, however, was consistent with the past research involving one-handed catching (Mazyn et al., 2006; Savelsburgh & van Santvoord, 1996). The data confirmed that the typically developing children formed a synergy between the elbow and wrist, as consistent with Latash's (2008) definition, to complete the task effectively, while the children with DCD did not.

The between group differences exhibited in this present study are consistent with Burton's model (1990). Prior research has revealed that children with DCD have difficulties performing actions involving inter-limb coordination of homologous and non-homologous limb pairs (e.g., Astill, 2007; Volman et al., 2006). The assumption underlying the study of coordination between limbs or limb pairs (total body) is that there are no difficulties in motor coordination at the intra-limb level. The inferences from the present study revealed that children with DCD in fact do have issues coordinating movements within a single limb. It was clear that children with DCD exhibited different coordination tendencies, particularly at the elbow-wrist joints. The inferences from this present study indicate that children with DCD organize movements similarly at the proximal joints, but not the distal ones. It could be that effective organization develops in a proximal to distal direction (Jensen et al., 1995).

In terms of individual constraints, it was determined that both soft and hard constraints impacted the way children with and without DCD solved the degrees of freedom problem. Compared to the typically developing children, the children with DCD tended to ineffectively *free* the wrist joint. In addition to soft constraints, torque modulation also impacted the nature of intra-limb coordination. As hypothesized, the children with DCD, compared to the typically developing children, exhibited less than optimal passive torque modulation at the distal joints. This difference in torque modulation is consistent with Bernstein's (1967) original hypothesis that the optimal movement organization is marked by the ability to utilize the reactive phenomenon. Children without DCD were able to utilize the reactive phenomenon, or passive torque, at each joint during the action, while the children with DCD could not. In terms of muscular torque, both groups presented similar utilization at the shoulder and elbow joints, but between group differences were particularly apparent at the wrist joint. Compared to the typically developing children, the children with DCD did not utilize passive torque at the wrist joint and instead, attempted to use primarily muscular torque to control the joint. It could be that movement effectiveness is jeopardized by torque modulation of the most distal joint (i.e., the wrist). The inferences from this thesis indicate that torque modulation is mature between the ages of 9 and 12 in typically developing children and still developing in children with DCD.

The purpose of this study was to determine whether or not lack of movement functionality in children with DCD, as compared to the typically developing children, was due to differences in the nature of coordination and torque modulation. From the results, it was evident that children with DCD solved the degrees of freedom differently than the comparison group. These between group differences could have been due to biomechanical constraints, more specifically joints involved and torque modulation. It was apparent that children with DCD exhibited less than optimal modulation of passive torque and this torque modulation tendency manifested as differences in elbow-wrist coupling. More importantly, decoupling the elbow-wrist was a limiter to the performance of children with DCD and was constrained by utilizing more active than passive torque at the wrist joint

Limitations

The first limitation is in regard to the nature of the task. There may have been a ceiling effect and if the task was harder (i.e., different trajectory of the ball or faster actions), more pronounced spatial and kinetic differences could have emerged. There was also a limitation in how torque was calculated. Torque was derived from displacement data. It is possible that some of the noise in the data could have been mixed in with the signal and not removed by the low-pass Butterworth filter. This can be overcome, however, by using a higher sampling frequency. This less than optimal filtering ultimately could have affected the magnitude of the correlation coefficients, as this noise would cause random changes in torque. In future research, it is recommended that a higher sampling frequency be used (i.e., 300Hz) or that torque be derived from accelerometers instead of passive reflective markers.. There are also some assumptions involved with deriving torque from kinematic data. One important assumption is that there is no agonist-antagonist co-contraction. This assumption could have been violated in this present study and future research should also include EMG data—even though this could impose another constraint on the action. In addition, there may be a more suitable measure of torque modulation, namely a non-linear method.

The last limitation to the study was the sampling criteria. In this present research, the children must have been at or below the 5th percentile for total impairment score as a result of the MABC. There was, however, no inclusion/exclusion criteria for the ball skills score. Upon the individual analysis (Appendix J), it was evident that only one child was below the 5th percentile and four of the participants were above the 15th percentile for total ball skills score. Because of this heterogeneity within the DCD group, this research may have been distinguishing coordination and torque modulation tendencies of two separate sub groups of children with

DCD—ball skills problems versus other issues. Also, the sample size was small in this present research, so inferences regarding the entire population of children with DCD are limited and might only be suitable for the recruited sample.

Future research

This thesis has demonstrated that future research regarding children with DCD can go in several new directions related to motor control. One potential research topic is to examine the coordination tendencies of certain sub groups of children with DCD. It could be that, if this task was used again, coordination differences may emerge within a sub-group of children with DCD (i.e., children with ball skills problems). Another progression from this study would be to examine an action in three dimensions, such as throwing, and determine the nature of coordination and particularly the underlying torque modulation tendencies. A non-orthogonal analysis of torque was put forth by Hirashima, Kudo, and Ohtsuki (2007) and this method could be used to analyze throwing in children with DCD. This study, however, would have to be preceded by research investigating and estimating/predicting anthropometric data (i.e., radius to center of mass, moment of inertia, and center of mass) of individual segments in three-dimensions of older children.

It could also be that children with DCD have difficulties with organizing mature synergies because of other underlying factors (i.e. neuromuscular constraints) rather than torque modulation. If the effect of passive torques on joint movement is seen as a perturbation, it can be argued that the lack of effective movements is at the muscular level. More specifically, no research has examined whether or not children with DCD have problems with adjusting the equilibrium point, or resting length, of the muscles during single or multi-joint actions. The last potential research area to be studied in children with DCD also relates to work completed by

Mark Latash's group at Pennsylvania State University (i.e., uncontrolled manifold). This present study used movement effectiveness as a marker for the performance variable in the task. Because of equipment limitations, a performance variable (such as fingertip orientation) could not be measured in this research. It would be interesting to investigate how children with and without DCD organize the relevant elemental variables to stabilize a performance variable (e.g., fingertip location) in a goal-directed task, such as catching, using the uncontrolled manifold approach put forth by Scholz and Schoner (1999).

Conclusion

Conceptually, the present work is in line with the leading joint hypothesis (Dounskaia, 2005), showing that the movement patterns exhibited by the children with DCD were less effective due to differences in torque modulation at the subordinate joints. In terms of how children with and without DCD solved the degrees of freedom problem, this research has shown that children with DCD have a universal tendency to decouple the joints, which is consistent with previous findings (Przysucha, 2011). Furthermore, their coordinative tendencies were less stable, meaning this group lacks the ability to organize a consistent movement pattern across time/trials. Thus, in terms of Burton's model, it appears that some children with DCD have issues organizing actions involving intra-limb coordination, due to less than optimal torque modulation at the distal joints. Some results of the present research, however, were not consistent with the findings of previous work (Przysucha, 2011). Typically developing children, compared to the children with DCD, exhibited tight coupling of the elbow-wrist, instead of both joint pairs. This difference could be explained by the fact that coordination may develop in a proximal to distal manner (Jensen et al., 1995). More specifically, it seems as though the transport phase of the catch may not be affected in children with DCD, but the honing, or fine adjustment, phase is. From a clinician's standpoint, it is suggested that children with movement problems should master goal-directed actions, both gross and fine motor skills, involving a single limb, before practicing actions involving higher levels of movement organization. In sum, it is evident that biomechanical constraints impact intra-limb coordination at the distal joints in children with DCD, and these constraints, along with other factors (e.g., less than optimal proprioception), are causing ineffective movement organization in goal-directed actions such as catching.

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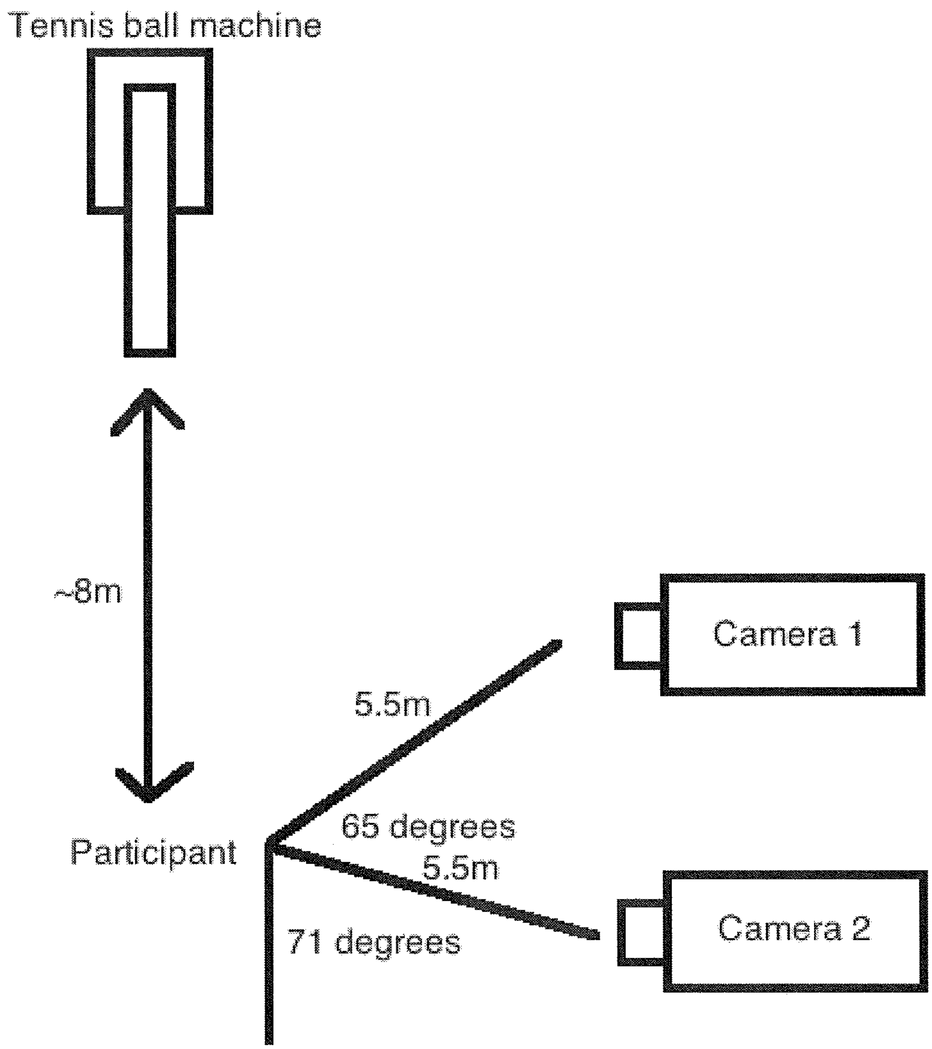
Appendix A

Task set-up


Tennis ball machine
~8m
Participant
5.5m
65 degrees
5.5m
71 degrees
Camera 1
Camera 2

Appendix B

Expansion of torque equations

three moments of inertia, $I_{1,1}$, $I_{2,2}$, and $I_{3,3}$,

$$\begin{aligned}
I_{1,1} &= I_1 + m_1 l_{c1}^2 + I_2 + m_2(l_1^2 + l_{c2}^2 + 2l_1 l_{c2} C_2) + I_3 + \\
&\quad m_3[l_1^2 + l_2^2 + l_{c3}^2 + 2l_1 l_2 C_2 + 2l_1 l_{c3} C_{12} + 2l_2 l_{c3} C_3] \\
I_{2,2} &= I_2 + m_2 l_{c2}^2 + I_3 + m_3(l_2^2 + l_{c3}^2 + 2l_2 l_{c3} C_3) \\
I_{3,3} &= I_3 + m_3 l_{c3}^2
\end{aligned} \tag{5.15}$$

and three coupling inertia terms, $I_{1,2}$ (which accounts for the effect on the torque at joint 1 of angular acceleration at joint 2), $I_{1,3}$, and $I_{2,3}$,

$$\begin{aligned}
I_{1,2} &= m_2(l_{c2}^2 + l_1 l_{c2} C_2) + I_2 + \\
&\quad m_3[l_2^2 + l_{c3}^2 + l_1 l_2 C_2 + l_1 l_{c3} C_{12} + 2l_2 l_{c3} C_3] + I_3 \\
I_{1,3} &= m_3[l_{c3}^2 + l_1 l_{c3} C_{23} + l_2 l_{c3} C_3] + I_3 \\
I_{2,3} &= m_3(l_{c3}^2 + l_2 l_{c3} C_3) + I_3
\end{aligned} \tag{5.16}$$

The centrifugal and Coriolis terms are

$$\begin{aligned}
v(\alpha, \dot{\alpha})_1 &= -[(m_2 l_1 l_{c2} + m_3 l_1 l_2)S_2 + m_3 l_1 l_{c3} S_{23}]\,(2\dot{\alpha}_1 \dot{\alpha}_2 + \dot{\alpha}_2^2) - \\
&\quad [m_3 l_1 l_{c3} S_{23} + m_3 l_2 l_{c3} S_3]\,(2\dot{\alpha}_1 \dot{\alpha}_3 + 2\dot{\alpha}_2 \dot{\alpha}_3 + \dot{\alpha}_3^2) \\
v(\alpha, \dot{\alpha})_2 &= -[(m_2 l_1 l_{c2} + m_3 l_1 l_2)S_2 + m_3 l_1 l_{c3} S_{23}]\;\dot{\alpha}_1^2 - \\
&\quad m_3 l_2 l_{c3} S_3 (2\dot{\alpha}_1 \dot{\alpha}_3 + 2\dot{\alpha}_2 \dot{\alpha}_3 + \dot{\alpha}_3^2) \\
v(\alpha, \dot{\alpha})_3 &= (m_3 l_1 l_{c3} S_{23} + m_3 l_2 l_{c3} S_3)\,\dot{\alpha}_1^2 + m_3 l_2 l_{c3} S_3 (2\dot{\alpha}_1 \dot{\alpha}_2 + \dot{\alpha}_2^2)
\end{aligned} \tag{5.17}$$

The gravity terms are

$$\begin{aligned}
G(\alpha)_1 &= m_1 l_{c1} g C_1 + m_2 g(l_1 C_1 + l_{c2} C_{12}) + m_3 g(l_1 C_1 + l_2 C_{12} + l_{c3} C_{123}) \\
G(\alpha)_2 &= m_2 g l_{c2} C_{12} + m_3 g(l_2 C_{12} + l_{c3} C_{123}) \\
G(\alpha)_3 &= m_3 g l_{c3} C_{123}
\end{aligned} \tag{5.18}$$

For planar chains with more than three links, the closed-form equations include many terms. These equations are derived with special computer programs. In three dimensions, the problem becomes even more perplexing.

Appendix C

Consent form for Director of Education and Principal

Child Participation Consent Form for Director of Education/Principal of School

I, ________________________________, agree for Mike Asmussen, a graduate student at Lakehead University, under the supervision of Dr. Eryk Przysucha, to recruit participants and conduct testing at the Schreiber and Terrace Bay Public schools. I have read and understood the parent information letter that outlines this research project. I am aware that there will be two testing sessions lasting 45 minutes each. During the first session, the participants will complete a set of tasks involving balance, catching/throwing, and manual dexterity. In the second session, the participants will attempt to catch 10 balls with his dominant hand at the speed of 7 m/s. I understand the potential risks and benefits of the children's participation in the study. I am aware that the children's participation is voluntary, the parents and children may refuse to answer any questions, and may withdraw from the study at any given time. I recognize that the participants' identity will be anonymous in any of the presentations or publications of the study because the researcher will use a number to replace each child's name. Dr. Eryk Przysucha will store the results of this data for 5 years at Lakehead University. I understand that the parents or children may access their own child's results, or the group's results by contacting the researcher any time after the study is completed.

Director's/Principal's Name:____

Signature:____Date:____________________

Appendix D

Typically Developing Children Recruitment Letter for Parents

Parent Information Letter

Title: Biomechanical Constraints on Coordination in Children with and without Movement Problems

Researcher: Mike Asmussen

Dear Potential Participant,

I, Mike Asmussen, a student at Lakehead University in the School of Kinesiology, invite your child to participate in a research study constituting a part of my Master's degree under the supervision of Dr. Eryk Przysucha. The purpose of this research is to see if there are differences in the way children with and without movement problems adapt their forces at the joints of the arm during an interceptive one-handed ball catching task. Your child is eligible for this study if he is male, between 9 and 12 years of age, and has typical visual acuity (20/20), or wears glasses/contacts to correct for less than optimal vision. In addition, your child must have no movement problems and a typical level of intelligence. Both of these characteristics will be determined by your answers on the attached consent form and Coordination Questionnaire.

The study involves your child attending two sessions at his respective school. Each session will last no longer than 45 minutes. During the first session, your child will complete the Movement Assessment Battery for Children, a formal evaluation tool, which determines your child's balance abilities (e.g., stork stand) catching/throwing, and manual dexterity (e.g., tracing). During the second session, your child will complete a one-handed catching task. I will start this session with a brief overview of the catching task, followed by a demonstration, and answer any questions your child may have. Your child will attempt to catch a tennis ball projected from a tennis ball machine at the speed of 7 m/s. This speed (7m/s) is similar to lobbing a ball underhand in a game of catch, thus will not cause your child any harm if he does not catch the ball. Your child will be asked to perform five practice trials followed by 10 acquisition trials.

I will use two high-speed cameras to capture your child's performance. I will place reflective markers on the dominant side of your child's body on the hip, shoulder, elbow, wrist, and fifth finger knuckle. These markers feel like having a small sticker attached to your arm. In addition, I will weigh your child (with a weight scale) and measure the length of his upper arm, forearm, and hand using a measuring tape.

If you wish for your child to participate, please fill out the attached consent form and the Developmental Coordination Disorder Questionnaire (DCDQ). Please have your child return the forms to his classroom teacher in the attached envelope. I will set-up times with the teacher to have your child complete the tasks during school hours.

Your child's participation is voluntary and your child may withdraw from the study at any time. You or your child may refuse to answer any questions that are asked in this research study. Your child's identity will remain fully confidential because I will replace the child's name with a number. This number will be used for any of the results in a paper or presentation. Only Dr. Przysucha and I will have access to results. These results will be held with Dr. Przysucha for five years at Lakehead University. If the data is needed for future research after the five years, the data will be kept securely with Dr. Eryk Przysucha. You and your child could view the individual, or group's results, after the study is complete by checking the box on the letter and providing your contact information.

There is no psychological or physical harm involved in your child participating in the study. The level of risk is no different than playing a game of catch. Your child can benefit from the study because he will have access to his own results, and if you or your child wishes, the group's results.

This research has been approved by the Lakehead University Research Ethics Board. If you have any questions/concerns regarding the ethics of the project, please contact the Board at 807-343-8283 or research@lakeheadu.ca.

Thank you for your time and considering your child's participation in this research.

Sincerely,

Mike Asmussen

Researcher's contact information

Mike Asmussen- Phone- 807-628-4666 or 807-343-8995

E-mail- **mjasmuss@lakeheadu.ca**

Dr. Eryk Przysucha- Phone- 807-343-8189

E-mail- **eprzysuc@lakeheadu.ca**

Appendix E

Typically Developing Children Consent Form for Parents

Child Participation Consent Form for Parents

I, _______________________________, agree for my child to participate in the research study being conducted by Mike Asmussen, a graduate student at Lakehead University, under the supervision of Dr. Eryk Przysucha. I have read and understood the information letter for this project. I am aware that there will be two testing sessions lasting 45 minutes each. During the first session, my child will complete a set of tasks involving balance, catching/throwing, and manual dexterity. In the second session, my child will attempt to catch 10 balls with his dominant hand at the speed of 7 m/s. I agree to complete the Energized Par-Q and Coordination Questionnaire to ensure my child is physically able to exercise and does not have any movement problems. I understand that my child must have 20/20 vision, or better, and if not, he must wear his corrective glasses/contact lenses for the testing sessions. I understand the potential risks and benefits of my child's participation in the study. I am aware that my child's participation is voluntary and he may withdraw from the study at any given time. I understand that I or my child may refuse to answer any questions asked in this research study. I recognize that my child's identity will be anonymous in any of the presentations or publications of the study because the researcher will use a number to replace my child's name. Dr. Eryk Przysucha will store the results of this data for 5 years at Lakehead University and if the data is needed for future research, it will be kept securely with Dr. Eryk Przysucha. I understand that I may access my child's, or group's, results by contacting the researcher any time after the study is completed.

Questions

1. Does your child have an Individual Placement and Review Committee (IPRC) at his school? Yes No (circle one)
    a. If yes, please state why:_______________________________
2. Does your child have any medical conditions that cause problems with his everyday movements (e.g., ADHD, Muscular Dystrophy)? Yes No (circle one)
    a. If yes, please state:_______________________________
3. Has your child ever been diagnosed with an intellectual disability? Yes No (circle one)
4. Does your child wear glasses or corrective lenses? Yes No (circle one)

Participant's Name:_______________________________ Participant's Age:__________

Parent/Guardian's Name:_______________________________

Parent/Guardian's Signature:_______________________________ Date:__________________

Child's Signature:_______________________________

Phone number:_______________________________

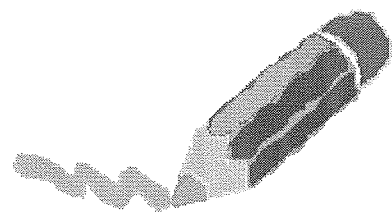
E-mail (optional):_______________________________

Please check this box if you wish to view your child's results ☐

Appendix F

Developmental Coordination Disorder Questionnaire

THE DEVELOPMENTAL COORDINATION DISORDER QUESTIONNAIRE 2007©
(DCDQ'07)



Wilson, BN, Kaplan, BJ, Crawford, SG, and Roberts, G
October 2007

Alberta Children's Hospital
Decision Support Research Team
2888 Shaganappi Trail NW
Calgary, Alberta, Canada T3B 6A8
http://www.dcdq.ca

DSET calgary health region Alberta Children's HOSPITAL FOUNDATION FACULTY OF MEDICINE | UNIVERSITY OF CALGARY

COORDINATION QUESTIONNAIRE (REVISED 2007)

	Year	Mon	Day
Today's Date:			
Birth Date:			
Child's Age:			

Name of Child: ______________________

Person completing Questionnaire: ______________________

Relationship to child: ______________________

Most of the motor skills that this questionnaire asks about are things that your child does with his or her hands, or when moving.
A child's coordination may improve each year as they grow and develop. For this reason, it will be easier for you to answer the questions if you think about other children that you know who *are the same age as your child*.
Please compare the degree of coordination your child has with other children of the same age when answering the questions.
Circle the one number that best describes your child. If you change your answer and want to circle another number, please circle the correct response twice.
If you are unclear about the meaning of a question, or about how you would answer a question to best describe your child, please call ______________________ at ______________ for assistance.

Not at all like your child	A bit like your child	Moderately like your child	Quite a bit like your child	Extremely like your child
1	2	3	4	5

1. Your child *throws a ball* in a controlled and accurate fashion.

   1 2 3 4 5

2. Your child *catches* a small *ball* (e.g., tennis ball size) thrown from a distance of 6 to 8 feet (1.8 to 2.4 meters).

   1 2 3 4 5

3. Your child *hits* an approaching *ball* or *birdie* with a bat or racquet accurately.

   1 2 3 4 5

4. Your child *jumps* easily *over* obstacles found in garden or play environment.

   1 2 3 4 5

5. Your child *runs* as fast and in a *similar* way to other children of the same gender and age.

   1 2 3 4 5

6. If your child has a *plan* to do a motor *activity*, he/she can organize his/her body to follow the plan and effectively complete the task (e.g., building a cardboard or cushion "fort," moving on playground equipment, building a house or a structure with blocks, or using craft materials).

   1 2 3 4 5 (OVER)

	Not at all like your child 1	A bit like your child 2	Moderately like your child 3	Quite a bit like your child 4	Extremely like your child 5

7. Your child's printing or *writing* or drawing in class is *fast* enough to keep up with the rest of the children in the class.

   1 2 3 4 5

8. Your child's printing or *writing* letters, numbers and words is *legible*, precise and accurate or, if your child is not yet printing, he or she *colors and draws* in a coordinated way and makes pictures that you can recognize.

   1 2 3 4 5

9. Your child uses appropriate *effort* or tension when printing or writing or drawing (no excessive *pressure* or tightness of grasp on the pencil, writing is not too heavy or dark, or too light).

   1 2 3 4 5

10. Your child *cuts* out pictures and *shapes* accurately and easily.

    1 2 3 4 5

11. Your child is interested in and *likes* participating in *sports or active* games requiring good motor skills.

    1 2 3 4 5

12. Your child learns *new motor tasks* (e.g., swimming, rollerblading) easily and does not require more practice or time than other children to achieve the same level of skill.

    1 2 3 4 5

13. Your child is *quick and competent* in tidying up, putting on shoes, tying shoes, dressing, etc.

    1 2 3 4 5

14. Your child would ***never*** be described as *a "bull in a china shop"* (that is, appears so clumsy that he or she might break fragile things in a small room).

    1 2 3 4 5

15. Your child does ***not*** *fatigue easily* or appear to slouch and "fall out" of the chair if required to sit for long periods.

    1 2 3 4 5

Thank you.

Decision Support Research Team
Alberta Children's Hospital
2888 Shaganappi Trail NW, Calgary, AB, Canada T3B 6A8
http://www.dcdq.ca

DSRT calgary health region Alberta Children's HOSPITAL FOUNDATION

COORDINATION QUESTIONNAIRE (DCDQ'07): SCORE SHEET

Name: ______________________ Date: ____________

Birth Date: ______________________ Age: ____________

	Control During Movement	Fine Motor/ Handwriting	General Coordination
1. Throws ball			
2. Catches ball			
3. Hits ball/birdie			
4. Jumps over			
5. Runs			
6. Plans activity			
7. Writing fast			
8. Writing legibly			
9. Effort and pressure			
10. Cuts			
11. Likes sports			
12. Learning new skills			
13. Quick and competent			
14. "Bull in shop"			
15. Does not fatigue			

TOTAL ___ /30 Control during Movement + ___ /20 Fine Motor/ Handwriting + ___ /25 General Coordination = ___ /75 TOTAL

For Children Ages 5 years 0 months to 7 years 11 months
- 15-46 indication of DCD or suspect DCD
- 47-75 probably not DCD

For Children Ages 8 years 0 months to 9 years 11 months
- 15-55 indication of DCD or suspect DCD
- 56-75 probably not DCD

For Children Ages 10 years 0 months to 15 years
- 15-57 indication of DCD or suspect DCD
- 58-75 probably not DCD

Decision Support Research Team
Alberta Children's Hospital

2888 Shaganappi Trail NW, Calgary, AB, Canada T3B 6A8
http://www.dcdq.ca

Appendix G

Child Par-Q for Parents

Energized
KiDS
CUSTOM EXERCISE PROGRAM

Exercise and Physical Activity Readiness Assessment
For Children and Adolescents

Important information for parents and guardians

The purpose of this form is to ensure that we provide every child and/or adolescent with the highest level of care. For most children, physical activity provides an opportunity for children and adolescents to have fun and promotes the basis for good health and an enhanced quality of life for the future. However there are a small number of children or adolescents who may be at risk when participating in an exercise/physical activity program. We would therefore ask that you read and complete this questionnaire carefully and return to the appropriate staff member. The information contained in this form is confidential and is subject to the laws and regulations contained in the Privacy Laws enacted in December 2001.

Personal Details

Name:____________________ DOB:____________ M/F:______
Height (cm):__________ Weight(kg):__________
How old was you child as at 1st January this year? ________
Name/s of Parent/s or Guardian/s:______________________________
Home Address:______________________________________
Home Contact Ph:__________Work Ph:__________Mobile PH:________
Has a GP or Specialist referred your child?__________
Doctor's Name: ____________ Contact Ph: ____________________
If there is an emergency, specify the person who should be contacted and their emergency phone number: Name:____________ Contact Ph: __________
Please Note: In case of a medical emergency, an ambulance may be used to transport your child to the nearest medical treatment service.

Heart-Lung-Other Systems

Does your child have, or has had:
A heart condition (please specify) ____________________________
Cystic Fibrosis
Diabetes (type 1 or Type 2 - please specify) ______________________
High blood pressure
High cholesterol

Coughing during or after exercise
Breathing problems or shortness of breath (eg: asthma)
Other (please specify) ____

Derived from The Children's Hospital Institute of Sports Medicine (CHISM)

Does your child experience or has your child ever experienced:
Epilepsy or seizures/convulsions
If yes, is it at rest or during exercise? ________________________________
Fainting
Dizzy spells
Heat stroke/heat related illness
Increased bleeding tendency/haemophilia
Other (please specify) ____
None of the above
If your child is taking any medication, please state if there are any side effects experienced as a result of taking this medication:

____

____

Muscle – Bone System
In the past 6 months, has your child had any muscular pain while exercising?
Yes **No**
If yes, please explain and indicate where the pain has occurred (eg "pain in the back of right heel" or "pain on the inside of the right elbow").____
Has a doctor treated this pain? **Yes** **No**
In the last 6 months, has your child experienced joint pain in the bones?
Yes **No**
If yes, please explain and indicate where the pain has occurred (eg: "front of right leg" or "behind my knee bone")

____

Special Conditions
1: Does your child use a "puffer" or "ventilator" for asthma?
Yes **No** **Not applicable**
2: Does your child have any chronic disability or chronic illness?
Yes **No**
If yes, please indicate condition:
Cerebral Palsy ***ADHD*** ***Downs Syndrome***
Hypermobility ***Intellectual impairment***

3: Are you aware of any medical reason/condition that might prevent your child from participation in an exercise program?
Yes **No**
If yes, please explain: ____

Informed Consent

I hereby acknowledge that:

- The information provided above regarding my child's health is, to the best of my knowledge, correct.
- I will inform you immediately if there are any changes to the information provided above.
- I give permission for my child to commence your physical activity program.

Parent/Guardian Signature: ___________________________ Date: _____________

Derived from The Children's Hospital Institute of Sports Medicine (CHISM)

Appendix H

Recruitment Letter for Parents of Children with Potential DCD

(Note: this letter is given to the parents during the meeting with the researcher)

Parent Information Letter

Title: Biomechanical Constraints on Coordination in Children with and without Movement Problems

Researcher: Mike Asmussen

Dear Potential Participant,

I, Mike Asmussen, a student at Lakehead University in the School of Kinesiology, invite your child to participate in a research study constituting a part of my Master's degree under the supervision of Dr. Eryk Przysucha. The purpose of this research is to see if there are differences in the way children with and without movement problems adapt their forces at the joints of the arm during a ball catching task. Your child is eligible for this study if he is male, between 9 and 12 years of age, a past or present member of the Motor Development Clinic, and has typical visual acuity (20/20), or wears glasses/contact lenses to correct for less than optimal vision. Your child must have movement problems that are not due to a known medical condition, but do interfere with his activities of daily living or academic achievement. In addition, your child must have a typical intelligence level. Your child's movement problems will be determined by your answers on the Coordination Questionnaire (attached) and if your child participates, his performance on a formal assessment called the Movement Assessment Battery for Children (MABC) (Henderson & Sugden, 1992).

The study involves attending only two sessions that will take place at Lakehead University, C.J. Sanders Fieldhouse, room SB-1028. Each session will last no longer than 45 minutes and you child will do the sessions independently. During the first session, your child will be required to complete the MABC, a formal evaluation tool, which determines your child's balance abilities, catching/throwing, and manual dexterity. During the second session, your child will complete a simple one-handed catching task. I will start the session with a brief overview of the catching task, give a demonstration, and answer any questions your child may have. Your child will attempt to catch a tennis ball projected from a tennis ball machine at the speed of 7m/s. This speed (7m/s) is similar to lobbing a ball underhand in a game of catch, thus will not cause your child any harm if he does not catch the ball. Your child will be asked to perform five practice trials followed by 10 acquisition trials.

To analyze the performance, I will use two high-speed cameras to capture your child's performance. I will place reflective markers on the dominant side of your child's body on the hip, shoulder, elbow, wrist, and fifth finger knuckle. These markers feel like having a small sticker attached to your arm. In addition, I will weigh your child (with a weight scale) and measure the length of his upper arm, forearm, and hand using a measuring tape.

If you are interested in your child participating, please fill out the attached consent form (including contact information) and Coordination Questionnaire. After this information is received, I will contact you via phone and provide you with available time slots for your child to complete the sessions. If the times are not convenient, I will make alternative arrangements. Your child's participation is voluntary and your child may withdraw from the study at any time. You or your child may refuse to answer any questions that are asked in this research study. Your child's identity will remain fully confidential because I will replace the child's name with a number. This number will be used for any of the results in a paper or presentation. Only Dr. Przysucha and I will have access to results. These results will be held with Dr. Przysucha for five years at Lakehead University. If the data is needed for future research after the five years, the data will be kept securely with Dr. Eryk Przysucha. You and your child could view the individual, or group's results, after the study is complete by checking the box on the consent form and providing your contact information.

There is no psychological or physical harm involved in your child's participation in the study. The level of risk is no different than playing a game of catch. Your child can benefit from the study because he will have access to his own results, and if you or your child wishes the group's results.

This research has been approved by the Lakehead University Research Ethics Board. If you have any questions/concerns regarding the ethics of the project, please contact the Board at 807-343-8283 or research@lakeheadu.ca.

Thank you for your time and considering your child's participation in this research.

Sincerely,

Mike Asmussen

Researcher's contact information

Mike Asmussen- Phone- 807-628-4666 or 807-343-8995

E-mail- **mjasmuss@lakeheadu.ca**

Dr. Eryk Przysucha- Phone- 807-343-8189

E-mail- **eprzysuc@lakeheadu.ca**

Appendix I

Consent Form for Parents of Children with Potential Movement problems

Child Participation Consent Form for Parents

I, ______________________________, agree for my child to participate in the research study being conducted by Mike Asmussen, a graduate student at Lakehead University, under the supervision of Dr. Eryk Przysucha. I have read and understood the information letter for this project. I am aware that there will be two testing sessions lasting 45 minutes each. During the first session, my child will complete a set of tasks involving balance, catching, and manual dexterity. In the second session, my child will attempt to catch 10 balls with his dominant hand at the speed of 7m/s. I agree to complete the Energized Par-Q to ensure my child is physically able to participate. I agree to fill out the Coordination Questionnaire to determine if my child potentially has movement problems that interfere with his activities of daily living or academic achievement. I agree that Dr. Taylor will inform the researcher if my child has ADHD or any other medical condition. I understand that my child must have 20/20 vision, or better, and if not, he must wear his corrective glasses/contact lenses for the testing sessions. I understand the potential risks and benefits of my child's participation in the study. I am aware that my child's participation is voluntary and my child may withdraw from the study at any given time. I understand that I or my child may refuse to answer any questions asked in this research study. I recognize that my child's identity will be anonymous in any of the presentations or publications of the study because the researcher will use a number to replace my child's name. Dr. Eryk Przysucha will store the results of this data for 5 years at Lakehead University and if the data is needed for future research, it will be kept securely with Dr. Eryk Przysucha. I understand that I may access my child's or group's results by contacting the researcher any time after the study is completed.

1. Does your child wear glasses or corrective lenses for vision problems?

   Yes No (circle one)

Participant's Name:______________________________ Participant's Age:__________

Parent/Guardian's Name:______________________________

Child's Signature:______________________________

Signature:______________________________ Date:____________________

Phone number:______________________________

E-mail (optional):______________________________

Please check this box if your wish to view your child's results ☐

Appendix J

Individual Results

Participant	Group	% Balls Caught	MABC TIS (%ile)	MABC TBS (%ile)	Shoulder-Elbow	Elbow-Wrist
1	w/o DCD	80%	89th	15th<	0.86	0.58
2	w/o DCD	100%	96th	15th<	0.47	0.77
3	w/o DCD	80%	70th	15th<	0.81	0.87
4	w/o DCD	70%	79th	15th<	0.57	0.61
5	w/o DCD	100%	29th	15th<	0.65	0.84
6	w/o DCD	80%	70th	15th<	0.74	0.92
7	w/o DCD	90%	65th	15th<	0.75	0.96
8	w/o DCD	80%	45th	15th<	0.77	0.97
9	N/A	N/A	N/A	N/A	N/A	N/A
10	w/o DCD	80%	54th	15th<	0.60	0.91
Group mean		85%	62.1	N/A	0.69	0.79
11	DCD	10%	1st	5th<	0.81	0.59
12	DCD	40%	1st	5th	0.78	0.43
13	DCD	10%	1st	15th<	0.86	0.74
14	DCD	60%	1st	15th<	0.94	0.75
15	DCD	60%	1st	15th<	0.76	0.26

16	DCD	10%	1st	5th	0.69	0.69
17	DCD	40%	1st	5th	0.75	0.87
18	DCD	0%	1st	5th	0.70	0.63
19	DCD	70%	2nd	15th<	0.92	0.53
20	DCD	20%	1st	5th>	0.77	0.85
Group Mean		32%	1.1	N/A	0.80	0.61

Note. MABC = Movement Assessment Battery for Children; TIS = Total Impairment Score; TBS = Total Ball Score

Appendix K

2d versus 3d coordinates

	Root mean square error of segments (m)			
Participant	**Trunk**	**Upperarm**	**Forearm**	**Hand**
1	0.0016	0.0150	0.0029	0.0012
2	0.3986	0.2085	0.2007	0.0698
3	0.0029	0.0029	0.0048	0.0015
4	0.0009	0.0144	0.0068	0.0018
5	0.0012	0.0282	0.0083	0.0024
6	0.0030	0.0156	0.0053	0.0027
7	0.0027	0.0067	0.0147	0.0011
8	0.0013	0.0106	0.0043	0.0009
9	N/A	N/A	N/A	N/A
10	0.0026	0.0030	0.0078	0.0030
11	0.0011	0.0104	0.0013	0.0014
12	0.0040	0.0141	0.0047	0.0026
13	0.0086	0.0079	0.0026	0.0014
14	0.0030	0.0071	0.0028	0.0027
15	0.0042	0.0229	0.0193	0.0033
16	0.0016	0.0285	0.0025	0.0042
17	0.0026	0.0054	0.0019	0.0012
18	0.0024	0.0136	0.0055	0.0021
19	0.0011	0.0128	0.0013	0.0016
20	0.0042	0.0076	0.0049	0.0030